SPATIAL MODELING OF MICROPLASTIC CONCENTRATION IN LAKE VOLTA

By

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DECLARATION

Student's Declaration

I, Collins Nana Andoh (UEPH0700121), hereby declare that, except for the references cited which have been duly acknowledged, this submission is my own work towards a Doctor of Philosophy in Environmental Engineering and Management, and that to the best of my knowledge, it contains no materials previously published by another person. I also declare that this has not been presented either in a whole or in part for another degree in this University or elsewhere.

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ABSTRACT

Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged over the past decade as one of the most pressing global environmental challenges, particularly in aquatic systems. While initial research has predominantly focused on marine environments, examining MPs in sediments, surface waters, and biota, it is now increasingly evident that freshwater ecosystems are equally vulnerable. MPs enter aquatic systems through land-based sources transported via rivers and streams, as well as contributions from fisheries and shipping activities. Although global attention to MPs in freshwater is expanding, significant research gaps persist in Africa, with Ghana's inland waters—especially Lake Volta—receiving minimal investigation despite their ecological and socioeconomic importance. Specifically, there is a lack of spatially explicit data on MP distribution, limited understanding of source-to-sink pathways in large tropical reservoirs, and inadequate integration of social practices with environmental contamination patterns in the region.

This study addresses these gaps through an innovative, multi-matrix spatial assessment that integrates household surveys, environmental sampling, and biological analysis within a unified analytical framework. Guided by the Pressure-State-Response (PSR) theoretical model, the research systematically examines human-induced pressures (solid waste management practices), environmental state (MP distribution in water and sediment), and biological impacts (bioaccumulation in fish), culminating in evidence-based response strategies. The study is further structured by a novel conceptual framework that maps the complete pollution pathway from land-based activities through aquatic transport to biological uptake, enabling holistic source attribution and risk assessment.

Key innovations include: (1) the first comprehensive spatial mapping of MPs across Lake Volta using GIS-based interpolation to identify pollution hotspots; (2) integrated sourceto-impact analysis linking household waste practices directly to environmental contamination and biological exposure; and (3) application of advanced spectroscopic techniques (ATR-FTIR) combined with ecological risk indices to quantify both immediate and long-term contamination threats.

Empirical findings revealed that solid waste mismanagement—a critical pressure—was widespread, with 40.0% of lakeshore households generating predominantly plastic waste, yet only 40.0% aware of waste segregation and 51.9% disposing of waste near their homes. Environmental analyses confirmed significant MP contamination, with average concentrations of 15.88 ± 10.69 MPs/L in surface water and 148.33 ± 119.35 MPs/kg in sediment, significantly higher in sediments ($p < 0.001$). Fibers and polyethylene dominated, with spatial hotspots identified in fishing-intensive zones (SII, SVI, SVII). Biological uptake was confirmed with 229 MPs detected in 96 fish specimens, averaging 2.47 ± 1.30 MPs per tilapia and 2.29 ± 1.73 MPs per catfish. MPs were negatively correlated with pH and dissolved oxygen, revealing physicochemical controls on distribution. While Ecological Risk Index (ERI) values (30.52 water, 27.44 sediment) indicated low immediate risk, Polymer Hazard Index (PHI) values (14.76 water, 13.02 sediment) signaled significant long-term contamination potential.

Collectively, these findings demonstrate that Lake Volta faces escalating MP pollution with clear ecological and socioeconomic implications. The study provides the first spatially explicit evidence base for MP contamination in Ghana's largest freshwater reservoir, offering novel insights into pollution drivers, distribution patterns, and biological transfer.

Informed by the PSR framework, urgent interventions—including strengthened waste management, targeted plastic recovery, community education, and spatially explicit monitoring—are required to safeguard fisheries, livelihoods, and water security in the Lake Volta basin. This research establishes a transferable methodological framework for assessing MP pollution in similar freshwater systems across West Africa.

DEDICATION

This work is respectfully dedicated to:

1. **Captain Peter Adansi Andoh**, my uncle, of blessed memory
2. **Obaapanyin Asi Kumiwaa**, my grandmother, of blessed memory
3. **Opanyin James Manu Kwabena Ampong (Master Ampong)**, my grandfather, of blessed memory
4. **Obaapanyin Esi Asieduaa (Alias Asi Kakraba)**, my grandmother
5. **Professor Akwasi Ayensu**, my uncle and academic mentor
6. **Professor Charles Buabeng-Andoh,** my uncle and academic mentor

In honour of their lasting values, steadfast support, and significant influence. My academic and personal journeys are still guided and inspired by their legacy.

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ABBREVIATIONS AND TERMINOLOGIES

MPs	Microplastics
POPs	Persistent Organic Pollutants
SDG	Sustainable Development Goal
GIS	Geographic Information Systems
PE	Polyethylene
PP	Polypropylene
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
PET	Polyethylene Terephthalate
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
HOCs	Hydrophobic Aromatic Contaminants
PCBs	Polychlorinated Biphenyls
PAHs	Polycyclic aromatic Hydrocarbons
UV	Ultra Violet
WWTPs	Wastewater Treatment Plants
ROS	Reactive Oxygen Species
µFTIR	Micro Fourier Transform Infrared Spectroscopy
P-GC/MS	Pyrolysis Gas Chromatography-Mass Spectrometry
ARGs	Antibiotic Resistance Genes
UNEP	United Nations Environment Programme
WWF	World Wide Fund
SWM	Solid Waste Management
EPR	Extended Producer Responsibility

OECD	Organisation for Economic Co-operation and Development
PPPs	Public-private partnerships
IDW	Inverse Distance Weighting
GWR	Geographically Weighted Regression
ML	Machine learning
RF	Random Forest
SVM	Support Vector Machines
ANNs	Artificial Neural Networks
PLI	Pollution Load Index
ERI	Ecological Risk Index
PHI	Polymer Hazard Index
DPSIR	Driving Forces-Pressure-State-Impact-Response
SES	Social-Ecological Systems
PSR	Pressure-State-Response
ANOVA	Analysis of Variance
PCA	Principal Component Analysis
CCA	Canonical Correspondence Analysis
ISO	International Organization for Standardization
WQP	Water Quality Parameters
Tilapia	Popular name used to represent *Cichlids* family
Catfish	Popular name used to represent Claris family

PUBLICATIONS AND CONTRIBUTIONS

1. **Chapter 3: Fourier Transform Infrared Spectroscopy: An analytical technique for microplastic identification and quantification**

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3. **Chapter 5: Charting pollution: spatial modeling of microplastics distribution in sediments and surface water from Lake Volta, Ghana, using ArcGIS**

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(Andoh et al. 2025b)

4. **Chapter 6: Distribution and Abundance of Microplastics in Tilapia and Catfish Species in Lake Volta, Ghana**

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5. **Chapter 7: Multi-matrix assessment of microplastics and physicochemical dynamics in Lake Volta**

Authors: Collins Nana Andoh, Nana Osei Bonsu Ackerson, Mary Antwi, Etornyo Agbeko, Kofi Adu-Boahen, Eric Kretsi

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background to the Study

Plastic pollution is a growing global environmental problem (Andoh et al. 2025a). This increase is mainly due to a rise in plastic production from 1.5 billion metric tonnes (BMT) in 1950, 8.3 BMT in 2018, and expected to reach 34 BMT by 2050 (Periyasamy & Tehrani-Bagha, 2022). Plastics, especially microplastics (MPs) – defined as particles smaller than 5 mm – have spread widely in both marine and freshwater ecosystems due to human activities such as fishing, poor waste management and urban runoff which are causing serious ecological, environmental and public health issues (Millet et al., 2018; Prasittisopin et al., 2023). Additionally, due to its modality, durability, and lightweight, plastic has been used widely in different fields such as packaging, construction, healthcare, fishing, and electronic and hence all over the place (Andrady & Neal, 2009).

In Ghana, increasing urbanization, ineffective solid waste management systems, and a lack of comprehensive policy enforcement has led to substantial plastic leakage into the environment (Kombiok et al., 2021; Macheca et al., 2024). This situation is particularly troubling in and around Lake Volta, one of the most important freshwater bodies in West Africa. Lake Volta serves as a vital resource for fishing, transportation, irrigation, and drinking water for millions of Ghanaians. However, the lake is under threat due to the accumulation of plastic waste that fragments into MPs (Acquah et al., 2021).

1.1.1. Overview of Lake Volta and Its Importance

Lake Volta, created by the Akosombo Dam on the Volta River in the 1960s, is one of the largest artificial lakes in the world by surface area (Braimah, 2003; van Zwieten et al., 2011). The Volta River system (also known as the Volta Basin), feeds Lake Volta, which traverses six West African countries, Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali and Togo and has other major tributaries like the Black Volta and the Oti River (Figure 1.1). It spans multiple regions in Ghana and supports many communities that depend on its resources for their livelihoods. The lake plays a crucial role in the economy, ecology, and water management of the area. It provides hydroelectric power, supports inland fisheries, boosts agriculture, and supplies domestic water.

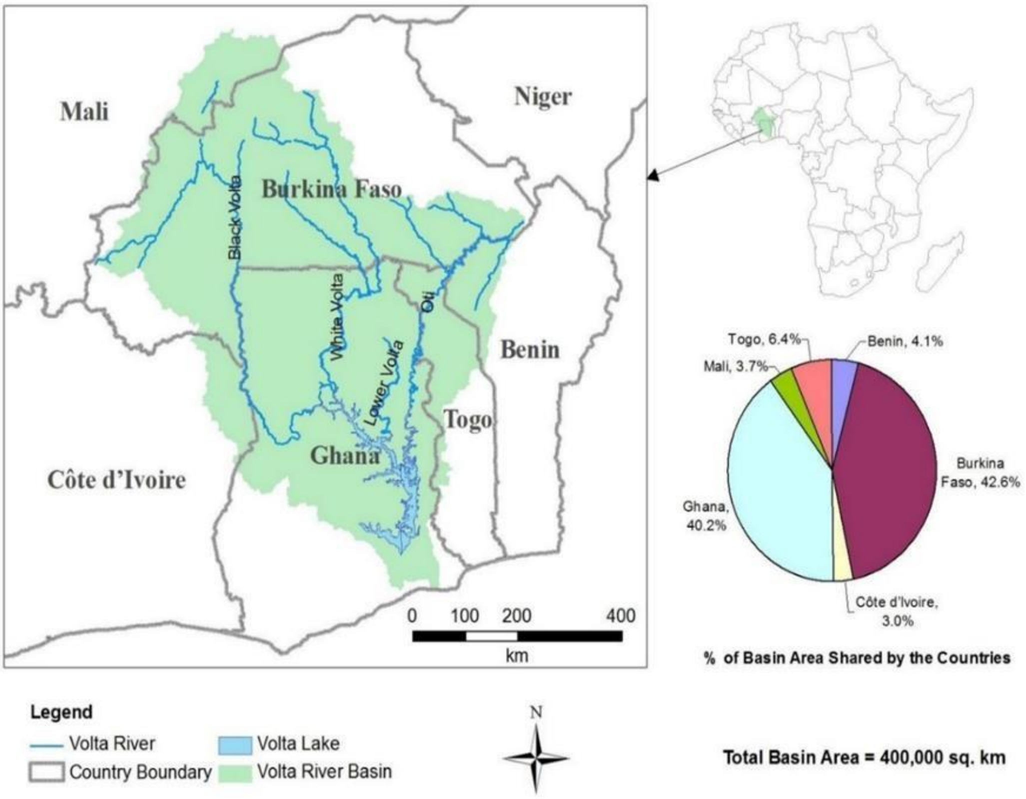

Figure 1.1: Volta Basin, showing political boundaries and essential tributaries (Kotir et. al, 2017)

Despite its significance, Lake Volta faces growing problems from environmental stressors, especially pollution from plastics and microplastics. Human activities like open dumping, unregulated fishing, tourism, and industrial waste contribute to the lake's pollution. These contaminants harm aquatic life and may pose health risks to people who drink water and eat fish from the lake.

The African continent has its own challenges with managing plastic waste because of the weakness of infrastructure and policies (Massa et al., 2024). African countries like Ghana, Kenya, and South Africa are witnessing a rise in plastic waste, which often accumulates in water bodies and urban areas. In Ghana, plastic waste is a major problem because of the inadequate post-consumer treatment and informal waste collection, and research indicates that most households poorly manage plastic waste (Kombiok et al., 2021). Waste pickers and the informal sector in general have taken central roles in plastic waste management, and efforts are being put to formalise them as part of the waste management sectors to boost recycling and decrease environmental impact. Global and regional organizations like the Global Plastic Action Partnership are progressively offering their auxiliary to the endeavors to address the plastic waste mismanagement issue. Nevertheless, key drivers of plastic pollution remain, specifically the sheer volume of plastic waste, gaps in the infrastructure for collection, recycling, and final containment, and the prevalence of an informal management sector that operates without the safeguards to prevent environmental leakage (Massa et al., 2024). There should be an effort to develop sustainable waste management systems with reference to governmental reforms, local involvement, and global assistance (Andoh et al. 2025a).

1.1.2. The Threat of Microplastics in Lakes

Microplastics pose a serious threat in freshwater environments such as lakes because they are persistent, widespread, and behave unpredictably in aquatic systems (Acquah et al., 2021). They come from breaking down larger plastic items (secondary MPs) or are made intentionally at tiny sizes (primary MPs).

A critical driver of microplastic pollution in freshwater systems like Lake Volta is the pervasive inadequacy of solid waste management infrastructure (Kaza et al., 2018). In Ghana, and particularly in the lakeshore communities, this manifests as limited waste collection services, a reliance on open dumping, and the widespread practice of burning refuse (Kombiok et al., 2021; World Bank, 2022). This infrastructural deficit creates a direct pathway for plastic waste to enter the environment, with a significant proportion of plastic waste being mismanaged globally (Jambeck et al., 2015). Larger plastic items, when improperly disposed of in open dumps or waterways, are exposed to solar UV radiation, physical abrasion, and chemical weathering (Andrady, 2017). These environmental stressors cause the plastics to brittle and fragment over time, generating secondary microplastics (Vermaire et al., 2017). These particles are then transported into the lake through surface runoff, wind, or direct disposal, establishing a continuous and diffuse source of contamination (Horton et al., 2017). Therefore, the inefficiencies in the waste management system are not merely a localised solid waste issue but a fundamental contributor to the loading and persistence of microplastics in the aquatic ecosystem of Lake Volta (Acquah et al., 2021; Boateng et al., 2024).

Once in the water, organisms, including zooplankton and fish, ingest microplastics. This can lead to physical injuries, a false sense of fullness, and toxic effects from absorbed pollutants. Microplastics can also carry harmful chemicals like persistent organic pollutants (POPs), heavy metals, and disease-causing microbes (Koelmans et al., 2019). These pollutants can build up in aquatic life and become more concentrated as they move up the food chain, potentially affecting human health. Studies have shown that Lakes worldwide are being threatened with the high level of microplastic loads (Egessa et al., 2020; Kumar et al., 2024; Xu et al., 2021).

1.2 Problem Statement

Despite an increase in the global awareness of MPs pollution, there is still little research on freshwater systems, especially in developing countries, like those in sub-Saharan Africa. Research on MPs in freshwater systems is scarce in Ghana, and Lake Volta, regardless of its ecological and socio-economic significance, has not been comprehensively investigated with regard to MPs pollution (Acquah et al., 2021).

The limited studies conducted by Boateng et al. (2024) and Bruce-Vanderpuije et al. (2025) just targeted the lower basin of the lake and the upper basin was not studied. Lack of spatially explicit data will impede efficient development of monitoring and mitigation measures. Moreover, it appears that the contemporary waste management frameworks fail to consider the MPs pathways and behaviours in an adequate manner (da Costa et al., 2020; Bank & Hansson, 2023). A spatial interpretation of the distribution of MPs in Lake Volta is important to define hotspots, source-sink interactions and inform policy. In this study, the author attempts to fill these information gaps with the help of geospatial and statistical modeling analysis. The framework for this study is shown in Figure 2.

1.3 Purpose of Study

The main purpose of this research is to carry out a spatial modeling analysis of MPs in Lake Volta. Specific objectives include:

1. To assess the solid waste management practices in households along Lake Volta.

2. To characterise the spatial distribution of microplastic concentrations in surface waters and sediments across along Lake Volta using ArcGIS.
3. To assess the spatial distribution and bioaccumulation patterns of microplastics in fish species (tilapia and catfish) from Lake Volta.
4. To investigate the relationship between environmental factors and MPs concentration.

1.5 Significance of the Study

This study addresses a major knowledge gap in MPs research within the Ghanaian context. By spatially modeling MPs concentrations in Lake Volta, it provides a new lens through which environmental managers and policymakers can understand and combat freshwater pollution. The findings will be valuable to institutions responsible for water resources management, environmental protection, and public health.

Furthermore, this research contributes to global efforts in achieving Sustainable Development Goal (SDG) 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), and SDG 14 (Life below Water), by providing location-specific data and modeling that can enhance MPs mitigation strategies.

By pioneering a spatially explicit modeling approach for MPs pollution in a large tropical reservoir such as Lake Volta, this research will (i) fill critical knowledge gaps in freshwater MPs science, (ii) provide a decision-support tool for environmental authorities and stakeholders, and (iii) contribute to global efforts aimed at mitigating plastic pollution in inland waters. The methodologies and findings may be transferable to similar reservoir systems in West Africa and beyond.

1.6 Scope and Delimitations of the Study

This study establishes the first comprehensive assessment of microplastic pollution in Lake Volta, Ghana, with defined spatial, temporal, and theoretical boundaries that shape both its contributions and interpretation.

1.6.1. Spatial Scope

The study was conducted within Lake Volta, spanning its major hydrological divisions as designated by the Food and Agriculture Organization for fisheries management. The spatial coverage extends approximately from **Latitude 6.20°N to 8.58°N and Longitude 0.78°W to 0.30°E**, encompassing the lake's main body, Afram Arm, Oti River inflow, and Volta Riverine sections. A stratified sampling design was employed, selecting **16 sampling stations** across eight strata, with two stations (upstream 'U' and downstream 'D') per stratum to ensure representative spatial coverage of shoreline communities where human activity interfaces directly with the aquatic environment.

Spatial Limitation: The study focused on discrete point locations at lakeshore communities rather than continuous lake-wide sampling. While spatial interpolation (IDW in ArcGIS) provides valuable distribution models between points, contamination gradients in unsampled offshore and pelagic zones are inferred rather than directly measured.

1.6.2. Temporal Scope

All field sampling for water, sediment, and fish was conducted during a **single campaign in January 2024**, within Ghana's primary dry season. This period was selected to establish baseline contamination levels under stable hydrological conditions with minimal surface runoff, allowing clearer attribution of MP contamination to local, ongoing sources rather than seasonal pulse events.

Temporal Limitation: The study provides a spatial "snapshot" under dry-season conditions and does not capture seasonal variability (wet vs. dry season) or inter-annual trends. Microplastic loads, transport pathways, and distribution patterns may differ significantly during the rainy season due to increased watershed runoff, riverine inputs, and altered hydrodynamic conditions.

1.6.3. Theoretical Framework Scope

This study employs the **Pressure-State-Response (PSR) framework** to structure its investigation, effectively linking human activities (pressure) to environmental contamination (state) and proposing evidence-based management actions (response). This framework provides a clear, policy-relevant structure for addressing the research objectives.

Theoretical Limitation: The use of PSR rather than the more comprehensive DPSIR (Drivers-Pressures-State-Impact-Response) framework represents a deliberate theoretical boundary. While PSR effectively identifies pressures and quantifies environmental state, it provides less detailed analysis of underlying socioeconomic and institutional drivers (e.g., market forces, governance structures) and does not explicitly separate environmental state from ecological or human health impacts. This choice maintained analytical focus on spatial and quantitative assessment but indicates an avenue for future interdisciplinary research integrating broader governance and socioeconomic analyses.

1.6.4. Methodological Scope

The research employs a **multi-matrix approach** (water, sediment, biota) with **integrated methodologies** including household surveys, environmental sampling, ATR-FTIR spectroscopic identification, GIS spatial modeling, and ecological risk assessment. This comprehensive approach enables source-to-impact analysis within a unified analytical framework.

Methodological Limitation: While ATR-FTIR provides reliable polymer identification, it has detection limits for particles <20 µm and may face challenges with mixed polymers or heavily weathered particles. The study's focus on two commercial fish species (tilapia and catfish) provides insights into key fishery resources but does not represent the entire aquatic food web.

1.7 Structure of the Dissertation

This dissertation is structured as a thesis-by-compilation, incorporating several published, submitted, and prepared manuscripts. The organization is designed to present a logical progression from the foundational context and literature review, through the core research findings, to the final synthesis and recommendations. The structure is as follows:

Chapter 1: General Introduction – This chapter establishes the broad context of microplastic pollution as a global environmental challenge, narrowing the focus to the specific problem in Lake Volta, Ghana. It outlines the research problem, states the purpose and specific objectives of the study, and discusses its significance and scope.

Chapter 2: Literature Review – This chapter provides a comprehensive critical review of the existing scientific literature pertinent to the study. It covers the sources, distribution, and impacts of microplastics in freshwater systems, the critical linkage with solid waste management, and the spatial modeling approaches used in pollution studies. The chapter also presents the theoretical (Pressure-State-Response) and conceptual frameworks that guide the research.

Chapter 3: Fourier Transform Infrared Spectroscopy: An Analytical Technique – This chapter, derived from a published paper, offers a detailed examination of the primary analytical technique used in this research. It reviews FTIR's application, advantages, and limitations compared to other methods for identifying and quantifying microplastics, establishing the methodological foundation for the subsequent empirical chapters.

Chapter 4: Assessment of Residential Solid Waste Management Practices – Based on a submitted manuscript, this chapter presents the findings of a mixed-methods study investigating the household-level drivers of plastic pollution around Lake Volta. It assesses waste composition, disposal practices, and community awareness, linking land-based human activities to potential microplastic leakage into the lake.

Chapter 5: Spatial Modeling of Microplastics Distribution in Sediments and Surface Water – This chapter, drawn from a published paper, constitutes a core output of the research. It quantifies and characterises microplastic pollution in Lake Volta's water and sediment, using ArcGIS for spatial interpolation to identify pollution hotspots and assess ecological risks.

Chapter 6: Distribution and Abundance of Microplastics in Tilapia and Catfish – This chapter, from a manuscript in preparation, investigates the biological uptake of microplastics. It analyses the abundance, characteristics, and bioaccumulation of microplastics in two key fish species, assessing the transfer of pollution into the aquatic food web.

Chapter 7: Multi-matrix Assessment of Microplastics and Physicochemical Dynamics – This chapter, also from a manuscript in preparation, integrates findings from the water, sediment, and biota matrices. It explores the relationships between microplastic concentration and key water quality parameters, providing a holistic understanding of the pollution dynamics within the lake's ecosystem.

Chapter 8: General Conclusion, Recommendations and Contribution of Research – The final chapter synthesises the major findings from all previous chapters, drawing overarching conclusions about the state of microplastic pollution in Lake Volta. It presents actionable recommendations for policymakers, managers, and communities, and summarises the original contributions of the research to knowledge.

This dissertation follows a logical progression from assessing pollution sources (Chapter 4), to quantifying environmental contamination (Chapter 5), to examining biological uptake (Chapter 6), and finally integrating findings across all matrices (Chapter 7). Each chapter builds upon the previous to provide a comprehensive understanding of microplastic pollution in Lake Volta.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Microplastic pollution has emerged as a critical global concern, increasingly affecting freshwater environments such as rivers, lakes, and reservoirs. While initial research emphasised marine ecosystems, recent studies underscore the pervasive and harmful presence of microplastics in inland waters (Li et al., 2023; Xu et al., 2024). Microplastics contribute to biodiversity loss, impair water quality, and present potential risks to human health. This chapter synthesises contemporary literature on microplastic pollution in freshwater ecosystems, examining its sources, impacts, distribution, and the theoretical and methodological tools used to investigate it.

2.2 Microplastic Pollution

Microplastics (MPs) are synthetic polymer particles smaller than 5 mm that originate from either a primary source manufactured at a microscopic scale for use in industrial applications, cosmetics, and personal care products or secondary sources, which result from the degradation of larger plastic debris due to mechanical, thermal, and photochemical processes (Bouwmeester et al., 2015; Andrady, 2017). These particles have become a ubiquitous environmental pollutant, present in virtually every aquatic system globally from surface waters and sediments to the deep sea and polar regions (Koelmans et al., 2022; Law & Thompson, 2014; Zhou et al., 2023;). Their persistence in the environment is attributed to the chemical stability and hydrophobic nature of their polymeric structure. Common types of polymers found in microplastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), each with distinct densities and degradation characteristics that influence their environmental behavior (Hartmann et al., 2019; GESAMP, 2019).

Microplastics are classified not only by polymer type but also by morphological characteristics, including fibres (from textiles and ropes), fragments (from broken plastic items), films (from bags and wrappers), foams (from packaging materials), and pellets (raw plastic feedstock). These features determine their transport pathways, settlement behavior, and interactions with organisms (Lusher et al., 2017).

Microplastics have a high surface-area-to-volume ratio and a hydrophobic surface that facilitates the adsorption of persistent organic pollutants (POPs), heavy metals, and hydrophobic organic contaminants (HOCs) like polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). These pollutants can desorb upon ingestion by aquatic organisms, increasing their internal toxic load (Koelmans et al., 2019; Wang et al., 2023; Rochman et al., 2013). Additionally, microplastics can physically harm organisms through abrasion, blockage of the digestive tract, and false satiation, leading to reduced energy intake, stunted growth, and impaired reproduction (Wright et al., 2013). Due to their small size, they are readily ingested by a range of aquatic organisms including zooplankton, bivalves, crustaceans, and fish, allowing them to enter and move up the trophic food web (Barboza et al., 2018; Prata et al., 2019a).

Emerging research has highlighted the ecological role of microplastics as substrates for microbial colonization, forming what is now termed the "plastisphere"—a novel ecological niche comprising diverse microbial communities (Amaral-Zettler et al., 2020). These microbial assemblages often include pathogens, opportunistic bacteria, and antibiotic-resistant genes (ARGs), posing a dual biological and chemical risk to aquatic life and potentially to humans (Pittura et al., 2018). Studies have reported the presence of virulent bacterial species such as *Vibrio spp.* on microplastic surfaces, raising concerns about disease transmission via aquatic food consumption (Zettler et al., 2013). Microplastics also interact with nanoplastics, plastic particles smaller than 100 nm, which have greater potential to cross biological membranes and elicit cellularlevel effects, including oxidative stress and genotoxicity (Mattsson et al., 2017; Sharma & Chatterjee, 2017). While the study of nanoplastics is still developing, their association with microplastics adds another layer of complexity to environmental risk assessments.

The influence of climatic variability on microplastic (MP) distribution is a critical and often underexplored dimension of pollution dynamics in freshwater reservoirs. In the Lake Volta basin, the pronounced seasonality of the West African monsoon governs a hydraulic regime characterized by cyclical pulses of fluvial inflow and prolonged periods of evaporative drawdown (Mul et al., 2015; Gebrechorkos et al., 2022). This hydrological seasonality acts as a principal vector and redistribution mechanism for MP pollution. High-intensity wet seasons generate substantial catchment runoff, mobilizing terrestrial plastic waste and delivering pulsed inputs of MPs into the lake via its major tributaries (Meijer et al., 2021). Conversely, the extended dry season and managed reservoir drawdown promote flow quiescence, enhancing particle settling and potentially re-mobilizing nearshore sediments, thereby creating a dynamic and nonuniform spatio-temporal pattern of MP accumulation (Blettler et al., 2018). Consequently, MP distribution maps represent a transient snapshot heavily conditioned by the specific hydro-climatic phase during sampling.

To accurately characterize MP pollution and its drivers, research methodologies must explicitly account for this temporal forcing. A robust analytical framework necessitates synoptic sampling campaigns stratified across key hydro-climatic seasons (e.g., peak discharge, recession, and low-flow periods) to capture the flux and redistribution of particulates (Talbot et al., 2022). Furthermore, geostatistical or hydrodynamic models predicting MP distribution should integrate relevant climatic and hydrological covariates—such as tributary discharge rates, precipitation indices, wind fields, and reservoir operating levels—as external drifts to improve spatial prediction accuracy and elucidate causal pathways (Robinson et al., 2021; Li et al., 2022). This synthesis of climatology, hydrology, and contaminant science is essential to differentiate between persistent anthropogenic point sources and transient, climate-driven accumulation zones, thereby advancing the research from descriptive mapping to a process-based, predictive understanding vital for adaptive resource management (Guo et al., 2024).

In summary, microplastics are not only chemically persistent but also biologically interactive pollutants. Their diverse sources, physical properties, chemical affinities, and biological interactions make them a multi-dimensional threat to freshwater and marine ecosystems. Their conceptualization requires an interdisciplinary understanding of materials science, toxicology, ecology, and hydrology.

2.3 Sources and Distribution of Microplastics in Freshwater Systems

Microplastics enter freshwater systems primarily through land-based anthropogenic activities, with both point and non-point sources playing significant roles. The major documented pathways of microplastics (MPs) into aquatic systems include wastewater effluent, stormwater runoff, atmospheric deposition, agricultural runoff, and mismanaged solid waste (Evangeliou et al., 2023; Ivleva, 2021). However, their relative contribution is highly context-dependent, varying with local infrastructure, land use, climate, and socioeconomic factors. Within the Lake Volta basin, mismanaged solid waste is likely the predominant and most direct pathway, with other sources playing secondary or less-defined roles.

2.3.1. Wastewater Treatment Plants (WWTPs)

WWTPs are one of the most thoroughly studied point sources of microplastic pollution. They contribute significantly to the release of synthetic microfibres from domestic laundering of textiles, especially those made from polyester, nylon, and acrylic (Liu et al., 2023a; Hidayaturrahman & Lee, 2019). Although advanced treatment technologies such as membrane bioreactors (MBRs) and rapid sand filtration can remove over 90% of MPs, a considerable number still escape into receiving waters or are transferred to terrestrial systems via biosolids application in agriculture (Corradini et al., 2021; Akarsu et al., 2023).

2.3.2. Urban Runoff and Road Dust

In urban environments, microplastics accumulate on surfaces such as roads, sidewalks, rooftops, and green spaces. During rainfall events, these particles are mobilised by stormwater and directed into nearby streams and rivers via storm drains (Sharma et al., 2021; Sharma & Chatterjee, 2017). Road wear particles, tire abrasions, and thermoplastics from line markings are increasingly recognised as significant contributors, particularly in high-traffic areas (Kole et al., 2017; Hale et al., 2020). This acts as a major secondary and seasonal amplifier. During the rainy season, runoff from communities, markets, and unpaved roads mobilises dispersed plastic litter and microplastics from the land surface, channeling them into the lake. While less studied in Ghana, global models indicate it is a significant transport vector (Evangeliou et al., 2023). Its contribution in the Lake Volta context is likely substantial but temporally variable, peaking during and after rainfall events and linking directly to the baseline pollution from mismanaged waste.

2.3.3. Atmospheric Deposition

Microplastics are also transported via atmospheric currents and deposited through dry or wet precipitation into freshwater bodies. Recent findings show atmospheric fallout as a major source, even in remote or mountainous freshwater ecosystems, suggesting long-range transport of lightweight microplastics (Allen et al., 2019; Brahney et al., 2021). This represents a pervasive but likely lower-load background pathway. Atmospheric fallout of MPs has been documented even in remote areas (Brahney et al., 2021). For Lake Volta, deposition from wind-blown dust and particles—originating from local waste burning, road dust, market centers or long-range transport—provides a continuous, diffuse input across the lake surface. While challenging to quantify and likely smaller in mass compared to direct runoff, it is a ubiquitous input that contributes to the baseline contamination.

2.3.4. Agricultural Sources

Agricultural practices contribute MPs through the use of plastic mulching, drip irrigation systems, and biosolid fertilisers derived from sewage sludge (Weithmann et al., 2018; Zhang et al., 2022). Irrigation canals and drainage networks serve as conveyance channels that move particles from farms into adjacent freshwater ecosystems. Its contribution is moderate but spatially variable. The Lake Volta basin supports significant agriculture. Potential MP sources include plastic mulching films (where used), soil amendments with biosolids, and irrigation water containing suspended particles (Boateng et al., 2024). However, compared to intensive horticultural systems, much of the surrounding agriculture may be less reliant on plastic agrofilms. Thus, this pathway may be significant in specific sub-catchments with commercial farming but less so in others.

2.3.5. Industrial and Commercial Sources

Industrial activities release microplastics directly through effluents, especially in plastic manufacturing, recycling, and textiles. Pre-production pellets (nurdles) and resin fragments often enter water systems due to poor handling or spills during transportation (Periyasamy & Tehrani-Bagha, 2022; Jiang et al., 2021). Similarly, microbeads from abrasive cleaning agents and cosmetic products may still be present in regions with weak enforcement of bans.

2.3.6. Solid Waste Mismanagement

Improper solid waste management remains a leading source of secondary microplastics in freshwater systems. Plastic waste left in open dumps, riverbanks, and urban gutters can fragment over time due to UV exposure, temperature fluctuations, and mechanical abrasion, ultimately forming microplastics that enter water bodies through wind or surface runoff (da Costa et al., 2020; Bank & Hansson, 2023). This is assessed as the primary pathway for Lake Volta. As documented through earlier regional analyses by Massa et al. (2024) and Kombiok et al. (2021), waste collection infrastructure in lakeshore communities is severely limited. Predominant practices of open dumping and burning of household waste—which is up to 40% plastic—at the shoreline create a permanent reservoir of plastic debris. This macrowaste undergoes continuous photodegradation and mechanical fragmentation, generating secondary microplastics that are directly washed into the lake by rain or wind. The proximity of disposal sites to the water and the lack of containment make this a high-efficacy, localised input pathway.

2.3.7. Hydrological and Spatial Variability

The distribution of microplastics is highly spatially heterogeneous, influenced by hydrological conditions, land use, topography, and anthropogenic activity. For instance, microplastic concentrations are typically higher in urban and peri-urban zones, particularly downstream of wastewater outfalls and densely populated settlements (Schmidt et al., 2017; Li et al., 2023).

Rivers act as dynamic conduits, transporting land-derived plastic debris over long distances and depositing them into lakes, reservoirs, and estuaries. Their transport capacity depends on flow velocity, sediment load, geomorphology, and rainfall patterns (Blettler et al., 2018; Wang et al., 2023).

2.3.8. Direct Aquatic Activities: Fisheries and Transportation

While not a land-based source, the intensive use of the lake for fisheries and transportation constitutes a direct in-situ pathway for MPs. Fishing contributes via lost or discarded gear (ghost nets, lines) that degrade into secondary MPs. Water transportation contributes through the wear of polymer-based vessel components (e.g., paint, ropes) and occasional operational losses. For Lake Volta, a hub of artisanal fishing and ferry traffic, these activities are likely a meaningful contributor to the overall MP load, especially in zones of high boat traffic and fishing intensity (Boateng et al., 2024).

In seasonal climates, storm events and rainfall can markedly influence microplastic fluxes by resuspending particles from sediments or introducing new loads from land surfaces (Xiong et al., 2021). In Lake Volta, Ghana's seasonal climate plays a central role in shaping microplastic dynamics. During the wet season (April–October), intense rains generate substantial runoff from lakeshore communities, delivering fresh inputs of plastic pollution to the lake. Increased tributary inflow and wind-driven wave action can also remobilise settled microplastics, redistributing them within the water column and altering their bioavailability. These processes indicate that the dry-season conditions documented in this study represent a baseline, with higher fluxes and potentially greater ecological risks expected during peak rainfall. Additionally, retention features such as floodplains, wetlands, and slow-flowing river bends may act as sinks for microplastics, particularly dense polymer fragments (Free et al., 2014).

Summary of Key Influences on Distribution

- Proximity to WWTPs, landfills, roads, and agricultural fields increase MP concentrations.
- High rainfall and flash floods mobilise microplastics into freshwater bodies.
- Rivers and drainage systems serve as both transport and transformation environments.
- Atmospheric fallout makes even pristine catchments vulnerable to contamination.

2.4 Microplastics, Water Quality, and Ecological and Human Health Impacts

Microplastics (MPs) are now recognised not only as physical pollutants but also as complex chemical and biological agents that significantly degrade the quality of freshwater systems. Their widespread presence in water columns, sediments, and aquatic biota reflects both chronic and acute environmental stressors that have cascading ecological and health effects.

2.4.1. Impact on Water Quality

Microplastics directly affect water quality by altering key physicochemical parameters. Their presence in aquatic systems increases turbidity, reduces light penetration, and disturbs photosynthetic activity among primary producers such as phytoplankton and submerged vegetation (Kumar et al., 2021). MPs also alter the thermal profile and flow dynamics of freshwater bodies by affecting the sedimentation rate and surface reflectivity (Chae & An, 2018).

Furthermore, microplastics act as vectors for adsorbing and concentrating contaminants such as heavy metals (e.g., cadmium, lead), pharmaceuticals, pesticides, and persistent organic pollutants (POPs) like PCBs and PAHs. These pollutants adhere to the hydrophobic surfaces of MPs and can remain attached over long periods, increasing their environmental half-life and promoting long-distance transport (Wang et al., 2023; Koelmans et al., 2016). When these contaminated particles are ingested by aquatic organisms, the associated pollutants can desorb in the digestive tract, exacerbating their toxicity.

In sediment-rich environments, MPs interfere with oxygen diffusion by clogging pore spaces, disrupting redox balance, and affecting microbial decomposition processes. This leads to anoxic conditions which reduce water quality and can trigger internal nutrient loading, contributing to eutrophication and harmful algal blooms (Zhang et al., 2020; Parker et al., 2022).

2.4.2. Ecological Impacts

Microplastics pose a serious threat to freshwater biota across trophic levels. Their small size makes them easily ingestible by plankton, insects, mollusks, and fish. Ingestion can result in gut blockage, false satiation, reduced nutrient absorption, and ultimately malnutrition, stunted growth, or mortality (Ferreira et al., 2022; Prata et al., 2023).

Additionally, MPs affect reproductive fitness, enzyme activity, and immune responses in aquatic organisms. For example, exposure to microplastics has been shown to reduce the fecundity of Daphnia magna (water fleas), impair the olfactory senses in fish, and alter swimming behavior—making organisms more vulnerable to predators (Barboza et al., 2018). Microplastics also serve as substrates for biofilm development and the colonization of pathogenic bacteria, which can disrupt microbial community structure and trophic interactions (Zettler et al., 2013; Ma et al., 2020).

Long-term ecological risks include biomagnification, where MPs and their associated contaminants accumulate up the food chain, and biodiversity loss, particularly among sensitive species with narrow ecological tolerances (Miller et al., 2020).

2.4.3. Human Health Impacts

The implications of microplastics for human health are increasingly being documented. MPs have been found in drinking water (both tap and bottled), table salt, fruits and vegetables, human placenta, and more recently, bloodstreams, indicating systemic exposure through ingestion, inhalation, and possibly dermal absorption (Senathirajah et al., 2021; Leslie et al., 2022).

Potential health effects include:

- Oxidative stress and inflammation, as microplastics generate reactive oxygen species (ROS) at the cellular level.

- Endocrine disruption, especially from plastic additives such as bisphenol A (BPA), phthalates, and flame retardants, which mimic or block hormone function.
- Gastrointestinal disturbance, caused by physical abrasion and immune reactions in the gut lining.
- Translocation to organs, including the liver, kidneys, and even brain, particularly by nanoplastics capable of crossing biological membranes (Vethaak & Legler, 2021; Besseling et al., 2014).

Although definitive clinical outcomes are still being studied, the precautionary principle is increasingly advocated, emphasizing the urgent need to reduce human exposure to MPs through improved water filtration, food safety regulations, and waste reduction policies.

Microplastics pose multi-faceted risks to freshwater ecosystems and public health. By impairing water quality, disrupting ecological balance, and entering human food and water supplies, they represent a composite environmental hazard. Their impacts are exacerbated by their ability to interact with and transport other pollutants, making them a critical focus for integrated pollution management. Continued research, public awareness, and regulatory reform are essential to mitigate these far-reaching consequences.

2.5 Research Gaps in Microplastic Pollution in Freshwater Systems

Although research on microplastic pollution has grown significantly in recent years, the majority of studies have focused on marine environments, leaving substantial knowledge gaps in freshwater ecosystems despite their vital role in water supply, food production, and biodiversity conservation (Li et al., 2022; Vethaak & Leslie, 2022).

Lake Volta, the main freshwater system and source of inland fisheries lack the needed research to be able to manage it (Acquah et al, 2021; Boateng et al., 2024; BruceVanderpuije et al., 2025). Meanwhile, the complexity of freshwater systems, coupled with diverse pollution sources and variable hydrological conditions, presents unique challenges that are yet to be fully addressed.

2.5.1. Standardization of Sampling and Analytical Protocols

One of the most pressing limitations is the lack of standardised methodologies for sampling, extracting, identifying, and quantifying microplastics in freshwater matrices (Müller et al., 2020). Variations in mesh sizes, sampling depths, digestion methods, and polymer identification techniques result in inconsistent data, making cross-study comparisons difficult and often unreliable (Cowger et al., 2020).

Recent initiatives such as the Global Harmonization Project on Microplastics aim to develop globally accepted guidelines, yet uptake remains slow across regions, particularly in developing regions (Lusher et al., 2022). The use of advanced techniques like pyrolysis-GC/MS, μFTIR, and Raman spectroscopy also remains limited due to cost and technical capacity constraints.

2.5.2. Data Gaps in Understudied Regions

Most microplastic studies are concentrated in Europe, North America, and parts of Asia, with significant geographic gaps in Africa, Latin America, Southeast Asia, and small island developing states (Rakib et al., 2025). These regions often suffer from poor waste management infrastructure, higher rates of plastic mismanagement, and increasing urbanization, all conditions conducive to microplastic pollution.

For instance, recent global modeling by Meijer et al. (2021) revealed that over 80% of plastic leakage into aquatic systems originates from just 1,000 rivers, many of which are located in low-income countries where empirical microplastic data remain scarce. Without region-specific data, it is difficult to develop targeted policy responses or evaluate local ecological risks.

2.5.3. Limited Understanding of Fate and Transport in Sediments and Pore Waters

While surface water studies are more common, the behavior of microplastics in sediment-pore water interfaces is poorly understood. This zone plays a crucial role in nutrient cycling, contaminant exchange, and benthic habitat health. Yet, few studies examine how microplastics settle, resuspend, degrade, or interact with benthic organisms in these layers (Mbachu et al., 2022; Zhang et al., 2022).

Furthermore, microplastics may become buried or stratified within sediment profiles, potentially serving as long-term pollutant reservoirs. Their interaction with microbial communities in sedimentary environments, especially those involved in nitrogen, phosphorus, and carbon cycling is another area requiring in-depth investigation (Mahmoud et al., 2021).

2.5.4. Emerging Contaminants and the Plastisphere

While the "plastisphere", the microbial biofilm on microplastic surfaces has been studied in marine contexts, its composition, behavior, and ecological consequences in freshwater remain underexplored. Recent findings suggest that these biofilms can harbor antibiotic resistance genes (ARGs) and human pathogens, potentially introducing novel risks into water systems (Pittura et al., 2018).

Understanding how environmental conditions (e.g., temperature, pH, salinity) shape plastisphere communities in freshwater bodies is essential, especially given rising concerns over antimicrobial resistance and waterborne diseases (Amaral-Zettler et al., 2020).

2.5.5. Limited Integration of Social, Economic, and Governance Dimensions

Microplastic research has been largely biophysical, with limited integration of socioeconomic and policy dimensions. There is a need for interdisciplinary frameworks that account for human behavior, regulatory structures, industrial practices, and cultural attitudes toward plastic use and disposal (Bettini et al., 2020).

Studies exploring how waste governance, consumer behavior, informal recycling systems, and environmental education influence microplastic leakage are still rare. Similarly, data on the effectiveness of bans, taxes, and circular economy interventions in reducing freshwater plastic pollution are limited (UNEP, 2021; WWF, 2022).

2.5.6. Microplastics as Part of a Complex Pollutant Cocktail

Microplastics rarely occur in isolation. They interact with other emerging pollutants, including pharmaceuticals, nanoplastics, pesticides, and industrial chemicals. Their role as carriers or facilitators of pollutant transfer in freshwater food webs is not fully understood and remains a high-priority research need (Koelmans et al., 2016; Horton et al., 2017; Vethaak & Leslie, 2022).

Despite rapid advances, critical research gaps remain in understanding the distribution, behavior, and impacts of microplastics in freshwater ecosystems. These include a lack of global data coverage, underdeveloped analytical standardization, insufficient risk assessment models for sediment environments, and weak integration of social and policy dimensions. Addressing these gaps requires a multi-sectoral and transdisciplinary approach that links environmental science with governance, public health, and technological innovation.

2.6 Solid Waste Management and Microplastic Linkage

Improper solid waste management (SWM) is one of the most critical upstream drivers of microplastic pollution in freshwater systems (Macheca et al., 2024; Kherdekar & Ade, 2024; Piyathilaka & Sirisena, 2024). Inadequate infrastructure, lack of enforcement, low public awareness, and weak regulatory frameworks in many urban and peri-urban areas have resulted in the uncontrolled accumulation of plastic waste in terrestrial environments, where it gradually breaks down into microplastics due to photooxidation, mechanical abrasion, and thermal degradation (Velzeboer et al., 2014; Kaza et al., 2018).

2.6.1. Urbanization and Plastic Leakage

Rapid urbanization in developing countries has outpaced the capacity of local authorities to provide comprehensive waste management services. Studies show that over 2 billion people globally lack access to basic waste collection, and 3 billion lack controlled disposal facilities, leading to high rates of open dumping and burning (UNHabitat, 2022; UNEP, 2021). These practices contribute not only to greenhouse gas emissions but also to the gradual fragmentation of plastics into microplastics that are easily transported into waterways via surface runoff and wind.

Recent assessments suggest that macroplastic pollution is a key precursor to microplastic generation in aquatic environments, particularly in river catchments adjacent to unmanaged landfills or illegal dump sites (van Emmerik & Schwarz, 2020).

Plastics exposed to UV light, rainfall, and friction undergo disintegration, creating a continual source of microplastics that infiltrate rivers, lakes, and reservoirs.

2.6.2. Mismanaged Plastic Waste and Global Emissions

According to Lebreton and Andrady (2019), more than 11 million metric tons of plastic waste enter aquatic ecosystems annually, with projections reaching 29 million metric tons by 2040 under a business-as-usual scenario. Much of this stems from poor plastic waste collection, unregulated dumping, and the absence of effective recycling systems. In low-income regions, plastic waste constitutes up to 70% of visible solid waste in public spaces and drainage systems (OECD, 2022; Jambeck et al., 2015).

Plastic packaging, sachets, disposable cutlery, and single-use shopping bags are particularly problematic due to their lightweight nature and short usage lifespan. Once discarded, they are prone to fragmentation and dispersal, especially during heavy rainfall and flash flooding events (Parker et al., 2022; Borrelle et al., 2020).

2.6.3. Circular Economy and Systemic Solutions

In response, the concept of a circular economy for plastics has gained prominence. This approach emphasises waste minimization, material recovery, and design for recyclability, with the aim of keeping plastic materials in use for as long as possible (Chamas et al., 2020).

Key strategies include:

- Source segregation and decentralised waste collection models.
- Extended Producer Responsibility (EPR) schemes that hold manufacturers accountable for post-consumer waste.
- Deposit-return systems and incentives for recycling.

- Eco-design innovations to eliminate hard-to-recycle packaging.

Countries like Rwanda, Chile, and Germany have implemented these models with measurable success, leading to reductions in plastic leakage and increases in formal recycling rates (WWF, 2022).

2.6.4. Role of Informal Sector and Public-Private Partnerships

The informal waste sector plays a vital but often unrecognised role in plastic recovery, particularly in cities across Africa, Asia, and Latin America. Empowering waste pickers through formal recognition, training, and integration into municipal systems can significantly enhance plastic waste collection and prevent leakage into water bodies (Ghosh et al., 2022).

Public-private partnerships (PPPs) have also emerged as effective models for enhancing SWM capacity, promoting investment in material recovery facilities (MRFs), and piloting scalable innovations such as mobile collection units and plastic-for-credit exchange programs (Kaza et al., 2018; UNEP, 2021).

2.6.5. Regulatory and Policy Gaps

Despite growing awareness, policy implementation and enforcement remain uneven. Many countries still lack specific legislation on microplastics or enforceable limits on plastic waste generation. Where regulations do exist, such as plastic bag bans or import restrictions they often suffer from weak monitoring, limited compliance, and lack of public engagement (OECD, 2022; Wang et al., 2023).

The global Plastics Treaty currently under negotiation at the United Nations presents a unique opportunity to harmonise efforts and establish binding commitments toward ending plastic pollution (UNEP, 2022). Effective global governance could support countries in strengthening their SWM systems and aligning their national strategies with international targets.

The linkage between solid waste management and microplastic pollution is clear and compelling. Without systemic improvements in waste handling from generation to disposal efforts to mitigate microplastic contamination in freshwater systems will remain incomplete. As plastics continue to infiltrate the environment, the transition to circular, inclusive, and enforceable waste management systems is not only urgent but essential. Collaborative solutions that involve government, industry, civil society, and the informal sector offer the best path forward.

2.7 Spatial and Computational Modeling Approaches for Microplastics

The increasing availability of spatial data and geospatial technologies has enabled researchers to develop robust tools for mapping, analyzing, and predicting microplastic pollution in aquatic environments. Spatial modeling not only enhances understanding of the distribution and transport of microplastics but also supports decision-making by identifying pollution hotspots, estimating pollution loads, and prioritizing intervention zones (Cai et al., 2023; Talbot et al., 2022).

2.7.1. GIS and Remote Sensing Applications

Geographic Information Systems (GIS) are extensively used to compile and visualise spatial datasets on land use, hydrology, waste sources, and population density, key factors influencing microplastic distribution. GIS platforms support the integration of environmental variables and spatial analysis of MP sources and concentrations in freshwater systems (Nizzetto et al., 2022; Wang et al., 2023).

Remote sensing, while not yet capable of directly detecting MPs in water, can effectively monitor indirect indicators such as land use change, urban sprawl, vegetation cover, and surface runoff patterns (Karakuş, 2023). These proxies are important for estimating potential microplastic loading in watersheds, especially in data-scarce or inaccessible region.

2.7.2. Geostatistical and Regression-Based Models

The use of geostatistical and regression models to analyze microplastics has gained significant attention. This highlights the value of spatial modeling techniques in environmental research. Several studies point out the benefits of geostatistical methods like kriging and co-kriging for predicting and adjusting pollutant data. These methods can also be applied to microplastics analysis. For example, algorithms based on multivariate regression-kriging (RK) show that combining regression models with geostatistical interpolation improves the accuracy of spatial predictions, as seen in radar data adjustment studies (Wang et al., 2020). Geostatistical techniques like Inverse Distance Weighting (IDW) and Ordinary Kriging are employed to interpolate MP concentrations at unsampled locations, offering spatial predictions and associated uncertainties, crucial for environmental risks assessment (Chen et al., 2020a; Li & Heap, 2014). Similarly, introducing spatial filtering methods into geostatistical frameworks has shown potential in enhancing model performance compared to other machine learning or regression models that rely on spatial proxies (McCord et al., 2022).

Regression analysis is crucial for modeling spatial variability and understanding how environmental factors affect microplastic distribution. Regression models, including generalised linear mixed models, have been proven effective in pollutant risk assessments, which shows their reliability in creating spatial models (Bertazzon et al., 2006). Moreover, integrating climate factors into multimodal regression models has been suggested to analyze seasonal changes in environmental pollutants, a strategy that could be used in microplastics research.

Combining geostatistical and regression techniques provides a strong method for addressing the complexities involved in microplastics distribution. For instance, using factor and descriptive analyses together with geostatistical models helps assess spatial variation in environmental pollutants, creating a flexible framework for microplastics analysis (Miletić et al., 2025). Additionally, validating Poisson cokriging as a generalised linear mixed model has shown its promise in predicting microplastic counts. However, prediction errors suggest that improvements are still needed.

In summary, the literature highlights how geostatistical and regression-based models complement each other in environmental spatial analysis. These methods facilitate detailed mapping, risk assessment, and understanding of factors affecting microplastic distribution. This supports better environmental management strategies. The integration of these approaches continues to develop, offering improved predictive abilities and deeper insights into the spatial dynamics of microplastics.

2.7.3. Machine Learning Modeling

Machine learning (ML) approaches such as Random Forest (RF), Support Vector Machines (SVM), and Artificial Neural Networks (ANNs) have emerged as powerful tools for predicting MP concentrations and sources using environmental, spatial, and socioeconomic variables (Dong et al., 2025; Lin et al., 2022). ML excels at capturing non-linear interactions and has been used to automate MP classification from spectroscopic data, enhancing lab efficiency (Khanam et al., 2025).

ML models are increasingly integrated with GIS and remote sensing to generate highresolution distribution maps and pollution hotspot analyses (Chatrabhuj et al., 2024).

Although they require large, high-quality datasets and face interpretability challenges, ML models provide scalable, data-driven insights for mitigation planning.

2.7.4. Hydrodynamic and Process-Based Modeling

To simulate the movement and fate of microplastics in freshwater systems, researchers employ hydrodynamic models (e.g., MIKE 21, Delft3D) that simulate water flow, sediment transport, and particle dynamics (Yin et al., 2022; Kim et al., 2022; Hoffman & Hittinger, 2016). These models help determine how microplastics travel, settle, or resuspend under various flow regimes and environmental conditions (Jalón-Rojas et al., 2019; He et al., 2024). Hydrodynamic models are especially critical for predicting temporal variations in microplastic dispersion due to storm events, seasonal changes, or anthropogenic disruptions such as dam releases or dredging. Coupling these with geostatistical models enhances their predictive accuracy.

Process-based models incorporate detailed MP characteristics—density, size, polymer type, biofouling—into simulations of advection, sedimentation, and degradation. These models are increasingly linked with watershed models and source-receptor frameworks to forecast long-term accumulation and evaluate intervention scenarios (Vilmin et al., 2020).

2.7.5. Lagrangian Transport Modeling

Lagrangian models track individual MP particles through space and time, offering detailed insights into their trajectories, accumulation zones, and residence times in aquatic systems (Daily & Hoffman, 2020). These models excel at simulating long-range transport and stochastic processes like vertical mixing or beaching (Lebreton et al., 2012; van Sebille et al., 2015).

Advanced applications incorporate variable MP properties (e.g., shape, biofouling) and couple with hydrodynamic models (e.g., ROMS, FVCOM) to achieve realistic simulations of MP movement in rivers and lakes (Zhou et al., 2021). Despite computational and data limitations, Lagrangian approaches offer powerful capabilities for source attribution and scenario testing.

2.7.6. Pollution Risk and Scenario Modeling

Advanced spatial modeling also supports scenario analysis and risk mapping, which allow decision-makers to test the impacts of different policy interventions or land use changes (Amoah & Gorsevski, 2025). For instance, risk indices such as the Pollution Load Index (PLI), Ecological Risk Index (ERI), and Polymer Hazard Index (PHI) are used to quantify pollution threats in specific locations (Islam & Cheng, 2024).

By integrating GIS with socio-economic and ecological indicators, researchers can create composite vulnerability maps to identify communities most at risk from plastic pollution and prioritise them for monitoring, cleanup, and policy action (Tran-Thanh et al., 2022).

Spatial modeling represents a powerful suite of tools for understanding and managing microplastic pollution in freshwater environments. From mapping current distributions to simulating future risks, these techniques offer critical insights for researchers, planners, and policymakers. As modeling capabilities expand through the integration of machine learning, remote sensing, and participatory GIS, spatial analysis will continue to play a central role in tackling one of the most pervasive pollutants of our time.

2.8 Theoretical Framework: Pressure-State-Response (PSR)

The Pressure-State-Response (PSR) model, originally developed by the Organisation for Economic Co-operation and Development (OECD) in 1993, remains one of the most widely used conceptual frameworks in environmental assessment and policy analysis. It provides a logical structure to understand how human actions affect the environment and how society responds to these changes. The PSR framework is particularly applicable to complex, multi-scalar challenges such as microplastic pollution in freshwater systems (OECD, 1993; Niemeijer& de Groot, 2008).

2.8.1. Pressure

"Pressure" refers to human-driven forces that exert stress on the natural environment. In the context of microplastic pollution, key pressures include:

- Overconsumption of single-use plastics
- Improper disposal and littering
- Inadequate solid waste management infrastructure
- Industrial discharges, urban runoff, and wastewater effluents

Global plastic production exceeded 390 million tonnes in 2021, with packaging and consumer goods accounting for the majority (PlasticsEurope, 2022). A significant proportion of this plastic ends up mismanagedopenly dumped or burned, particularly in low- and middle-income countries, where solid waste collection coverage is below 60% in many urban areas (Kaza et al., 2018; UN-Habitat, 2022).

These human activities exert increasing pressure on freshwater ecosystems by introducing both macroplastics and microplastics that disrupt ecological processes and contaminate water resources (Borrelle et al., 2020).

2.8.2. State

The "state" reflects the current condition of environmental systems under the influence of these pressures. In the case of microplastics, this includes:

- The accumulation of plastic debris in freshwater bodies
- Alteration of water quality parameters
- Bioaccumulation in aquatic flora and fauna
- Transformation of sediment structure and microbial communities

Scientific investigations have detected microplastics in a wide range of freshwater compartments, including surface water, sediment, biota, and even drinking water (Leslie et al., 2022; Li et al., 2023). These particles often carry adsorbed toxic substances, such as heavy metals, POPs, and pharmaceuticals, which intensify their ecological and human health risks (Koelmans et al., 2016)

Furthermore, the presence of microplastics is increasingly being used as a proxy indicator of environmental degradation, supporting early warning systems for ecosystem stress (Xu et al., 2023; Mbachu et al., 2022).

2.8.3. Response

"Response" includes the institutional, societal, and technological actions taken to mitigate or adapt to the observed environmental changes. In the context of microplastics, responses span a wide spectrum:

- Policy and regulatory actions such as plastic bans, taxation, and Extended Producer Responsibility (EPR) schemes (UNEP, 2022)
- Technological innovations in biodegradable plastics, advanced wastewater filtration, and plastic recycling infrastructure
- Public awareness campaigns and behavior change initiatives promoting sustainable consumption
- Citizen science and participatory monitoring of plastic pollution (Varela et al., 2023)

At the global level, negotiations for a UN Treaty on Plastic Pollution aim to establish legally binding commitments by 2024, targeting the full lifecycle of plastics from production to disposal and environmental leakage (UNEP, 2022). National and local responses are also being scaled up, with countries like Rwanda, Chile, and the EU demonstrating effective policy frameworks that integrate prevention, reduction, and recovery strategies (WWF, 2022).

From a modeling perspective, integrating spatial and risk-based indicators within the PSR framework allows for more granular and actionable insights. Recent applications combine GIS-based pollution maps, risk indices (e.g., Ecological Risk Index, Polymer Hazard Index), and socio-economic vulnerability data to inform targeted interventions (Zhao et al., 2022).

2.8.4. Strengths and Limitations of the PSR Framework

The PSR model's strength lies in its simplicity and adaptability, making it useful for various stakeholders from scientists and policymakers to educators and civil society. It facilitates interdisciplinary collaboration and supports the design of integrated environmental monitoring programs (Niemeijer& de Groot, 2008; Vethaak& Leslie, 2022).

However, some critiques point to its linear cause-effect logic, which may oversimplify the feedback loops, delays, and system complexities inherent in environmental processes. For this reason, expanded models like DPSIR (Driving Forces-PressureState-Impact-Response) and social-ecological systems (SES) frameworks are increasingly used to capture a broader range of human-environment interactions (Kristensen, 2004; Rocha-Santos et al., 2022).

The Pressure-State-Response framework offers a valuable lens through which to conceptualise and address the microplastic pollution crisis in freshwater systems. By mapping human-induced pressures, assessing their environmental impacts, and evaluating societal responses, PSR provides a policy-relevant, evidence-based tool for shaping sustainable water governance strategies. Its integration with spatial analysis and ecological risk assessment makes it especially suitable for advancing both local action and global cooperation in managing plastic pollution.

2.9 Conceptual Framework

The conceptual framework for this study, Figure 2.1, shows how microplastics (MPs) come about, their movement, distribution, and accumulation in various parts of Lake Volta's environment. It also looks at the role of water quality factors and ecosystem health. This helps us understand the complex relationships between human pollution, water bodies, and biological uptake.

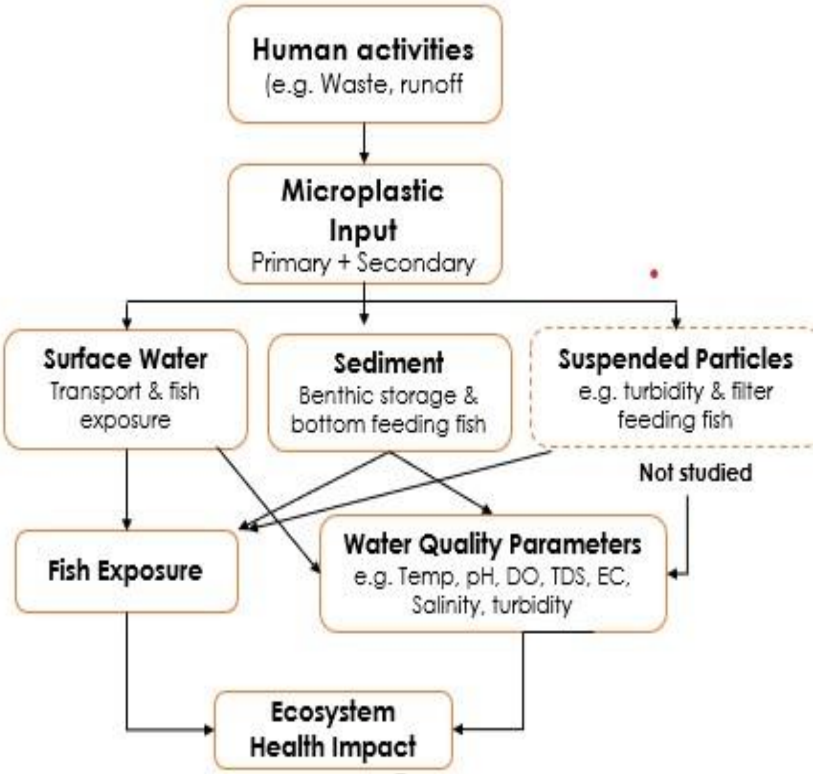

Figure 2.1: Conceptual Framework of the Study

At the top of the framework are human activities, such as urban waste disposal, agricultural runoff, and industrial discharge. These activities are the main drivers of microplastic pollution, putting plastics into the environment either directly as primary microplastics, like microbeads and pellets, or indirectly when larger plastics break down into secondary microplastics. These inputs mark the first point of contamination for freshwater systems.

Once in the environment, microplastics spread across several areas, including:

Surface Water: This is a main medium for MP transport, allowing them to disperse laterally and vertically. MPs can stay suspended, float, or settle based on their physical and chemical traits and local conditions.

Sediment: This acts as a sink for MPs. Over time, particles settle and gather in benthic layers, where they might stay buried or be resuspended if the flow or conditions change.

Fish (Biota): Fish represent a point for biological accumulation. They ingest microplastics directly from the water or indirectly through the food chain. This ingestion is affected by their feeding habits, species behavior, and the number of suspended particles nearby.

A separate but related path in the framework is the role of suspended particles—like detritus, silt, and organic matter—that add to turbidity. These particles can group with microplastics, helping them settle or spread in the water. High turbidity raises the likelihood of fish ingesting MPs, as the particles reduce visibility and make it hard for fish to tell food from non-food items.

The framework also includes water quality parameters that either affect or are affected by microplastics. These include:

Temperature (°C): This influences how quickly polymers break down and how the water column layers.

pH: This changes the surface charge of MPs and affects how contaminants stick to or release from them.

Dissolved Oxygen (DO, mg/L): These are vital for aquatic life and can be affected by MP-induced microbial growth or decay that demands oxygen.

Electrical Conductivity (µS/cm) and Salinity (ppt): These measure ionic strength and can influence how MPs behave and interact chemically.

Total Dissolved Solids (TDS, mg/L): These show particle loads that often relate positively to MP concentrations.

These physicochemical factors are measured in situ at each sampling site and help provide essential context for understanding the conditions under which microplastics last, move, or accumulate in organisms.

All pathways lead to one main outcome: the impact on ecosystem health. Microplastic pollution, shaped by water quality, can cause various ecological effects, like physiological stress in aquatic life, disruption of food webs, habitat degradation, and potential risks to human health through contaminated water or fish.

This multi-matrix, multi-pathway conceptual framework highlights the importance of a combined approach to assessing freshwater pollution, especially in areas lacking data like sub-Saharan Africa. It supports the study's goal of connecting MP levels in different areas (water, sediment, and fish) with water quality indicators to assess the extent and effects of pollution in Lake Volta.

2.10 Methodologies in Microplastic Pollution Research

Research on microplastics in freshwater environments has evolved significantly, driven by the need for standardised, reproducible, and scalable methodologies. A robust methodological framework typically involves sampling, extraction, identification, quantification, and data analysis, tailored to the specific environmental matrix (water, sediment, or biota). Recent advances have introduced automation, machine learning, and multi-matrix integration into microplastic studies, improving both accuracy and efficiency.

2.10.1. Sampling Techniques

Sampling is the foundational step in microplastic research, and the choice of technique significantly influences study outcomes (Koelmans et al., 2019; Cowger et al., 2020).

Common sampling methods include:

- Surface Water Sampling:
    - Grab sampling (discrete water collection using bottles or jars) remains widely used due to its simplicity and low cost. ○ Manta trawls and neuston nets (usually with 333 µm mesh size) allow for bulk surface water collection over transects, particularly in large water bodies (Masaru et al., 2015; Cowger et al., 2020).
    - Pump filtration systems are used for small-scale and depth-stratified sampling and are increasingly favored for collecting particles <300 µm (Li et al., 2022).
- Sediment Sampling:
    - Techniques include sediment coring, Ekman grabs, and Van Veen grab samplers, with layers preserved to assess vertical distribution of microplastics (Xu et al., 2021). ○ Sieving and density separation using, sodium chloride, zinc chloride or sodium iodide solutions are employed to extract plastics from sediment. • Biota Sampling:
    - Common in fish, bivalves, and invertebrates through gastrointestinal tract dissection or whole-body digestion. ○ Protease or hydrogen peroxide digestion is applied to remove organic matter before microplastic analysis (Lusher et al., 2017; Prata et al., 2019b).

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- Atmospheric Deposition and Catchment Runoff:
  - Dry and wet deposition samplers are increasingly used in studies of microplastic fallout onto freshwater surfaces (Allen et al., 2019).

.2. Identification and Quantification Techniques

Following sampling, microplastics are separated and identified through a combination of visual and instrumental techniques:

- Visual Sorting:
  - Stereomicroscopes are used to classify particles based on size, shape, and color. However, this method is subjective and limited for particles <500 µm (Cowger et al., 2020).
- Spectroscopic and Thermoanalytical Methods:
  - Fourier-transform infrared spectroscopy (FTIR) and Raman microscopy are widely used for polymer identification. Micro-FTIR allows for detection of particles as small as 20 µm, while Raman microscopy can identify nanoplastics <1 µm (Prata et al., 2019b; Xu et al., 2023).
  - Pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) and thermal extraction desorption-GC/MS (TED-GC/MS) are used for bulk chemical characterization of polymer types and additives (Dümichen et al., 2020).

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- Fluorescent Labeling and Imaging:
    - Nile Red staining combined with fluorescence microscopy is used to detect and semi-quantify microplastics in complex matrices like sludge or wastewater (Shim et al., 2016).
- Automated Image Analysis:
    - Software like MP-VAT, siMPle, and OpenSpecy now support automated classification of microplastic types, improving consistency and throughput (Cowger et al., 2020).

.3. Data Analysis and Statistical Modeling

Quantitative data generated from microplastic studies require comprehensive statistical treatment to identify patterns, correlations, and potential pollution sources:

- Descriptive Statistics: Used to report mean concentrations, size distributions, polymer types, and abundance per volume/mass (Zhang et al., 2020).
- Inferential Statistics:
    - Tests such as ANOVA, Kruskal-Wallis, and Mann-Whitney U assess differences between sites or temporal changes. ○ Correlation and regression analyses (e.g., Pearson, Spearman, multiple regression) link microplastic abundance to environmental or

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anthropogenic variables (Xu et al., 2023).

- Multivariate Techniques:
    - Principal Component Analysis (PCA), Cluster Analysis, and Canonical Correspondence Analysis (CCA) help reduce dimensionality and identify pollution sources or grouping trends (Mai et al., 2023).
- Spatial Modeling:
    - GIS tools, Kriging, and Geographically Weighted Regression (GWR) are applied to visualise spatial variability and identify hotspots of microplastic contamination (Chen et al., 2020a).
- Ecological Risk Assessment:
    - Indices such as Pollution Load Index (PLI), Ecological Risk Index (ERI), and Polymer Hazard Index (PHI) are increasingly used to quantify potential environmental harm (Islam et al., 2023).

.4. Standardization and Protocol Harmonization

Inconsistencies in microplastic research methods continue to hinder global data synthesis and meta-analysis. Efforts by institutions such as the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), ISO (International Organization for Standardization), and national research councils are driving the development of standardised protocols.

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Recent harmonization guidelines (Cowger et al., 2020; GESAMP, 2021) recommend:

- Clear reporting of sample volumes/masses, mesh sizes, and limit of detection
- Use of polymer reference libraries for spectral analysis
- Routine implementation of quality assurance and contamination control measures

The methodologies used in microplastic research have advanced considerably, integrating both traditional field techniques and state-of-the-art analytical tools. As detection methods become more sensitive and data analysis more sophisticated, the field is increasingly capable of capturing the complexity and multidimensionality of microplastic pollution. However, continued efforts toward standardization, automation, and capacity-building in under-resourced regions are essential for producing globally comparable and policy-relevant data.

2.11 Summary

This chapter has critically reviewed the growing body of literature on microplastic pollution in freshwater systems, synthesizing current understanding across several dimensions. It began by conceptualizing microplastics as persistent, synthetic polymer particles derived from primary and secondary sources, emphasizing their diverse forms, chemical properties, and ability to interact with pollutants and biological systems.

The review highlighted the varied sources and distribution patterns of microplastics, notably from land-based activities such as wastewater discharge, urban runoff, agricultural inputs, industrial effluents, and solid waste mismanagement. Key factors influencing their spatial variability include land use, hydrology, population density, and proximity to pollution sources.

Microplastics were shown to significantly degrade water quality by altering physicochemical parameters and transporting toxic substances. Their ingestion by aquatic organisms leads to physiological harm and bioaccumulation, posing ecological risks to food webs and human health threats via seafood consumption and contaminated drinking water.

Despite progress, the review identified notable research gaps: inconsistent methodologies, lack of standardised protocols, underrepresentation of tropical and lowincome regions, and limited understanding of sedimentary processes and socioenvironmental interactions. These gaps hinder effective global monitoring and policy development.

The role of solid waste management emerged as a pivotal factor in preventing microplastic formation. The transition to circular waste systems, improved waste collection, and regulatory reforms—such as Extended Producer Responsibility (EPR) and plastic bans—are essential strategies to reduce plastic leakage into freshwater systems.

Spatial modeling tools, including GIS, Kriging, and Geographically Weighted Regression (GWR), were recognised as powerful techniques for identifying pollution hotspots, predicting transport pathways, and informing risk-based decision-making. The integration of spatial data enhances the effectiveness of environmental monitoring and governance.

The Pressure-State-Response (PSR) framework was adopted to theoretically anchor the study, offering a structured lens to link human pressures with ecological conditions and policy responses. Its adaptability to spatial and risk-based indicators makes it suitable for microplastic research and management.

Finally, the review explored methodological advancements, covering sampling, identification, quantification, and statistical analysis. Emphasis was placed on harmonizing techniques to improve global data comparability and support evidencebased policy and research collaborations.

Collectively, the literature underscores the multidimensional threat posed by microplastics and the urgent need for coordinated scientific, regulatory, and community-driven responses to protect freshwater ecosystems and human health.

CHAPTER THREE

Fourier Transform Infrared Spectroscopy: An Analytical Technique for Microplastic Identification and Quantification

Abstract

Microplastics (MPs) have become the a major globally environmental concern and hence taken the center stage of major research works especially in the environmental sector. In this study, the sources, types, and effects of microplastics are examined. The paper also reviews the Fourier transform infrared (FTIR) spectroscopy and its use in identifying and quantifying microplastics in environmental samples compared with other analytical techniques. There is also a critical look at the advantages and drawbacks of FTIR for microplastic analysis, including its ability to identify and describe microplastics in a variety of environmental matrices compared with other viable analytical methods commonly used for microplastics identification. There was also a highlight on the current research and development efforts aimed at improving FTIR techniques for microplastic analysis, particularly low-concentration quantification. However, of all the techniques, the FTIR method is seen as an excellent tool especially in detecting functional groups in environmental samples and assessing microplastics amounting to several studies either using it solely or in addition with other techniques.

3.1. Introduction

FTIR (Fourier Transform Infrared Spectroscopy) is a powerful analytical method for identifying materials by analyzing infrared absorption spectra (Campanale et al., 2023; Fadlelmoula et al., 2022; Luo et al., 2022; Lee & Chae, 2021; Fadare et al., 2021; Veerasingam et al., 2020a; Thomas et al., 2017; Shim et al., 2017; Smith, 2014; Smith, 2011). The method has been used in microplastic identification since the turn of the century (Veerasingam et al., 2020a; Kedzierski et al., 2019; Thompson et al., 2004). The first time in history the technique was employed was when Thompson et al. used the new method for analyzing microplastics in marine sediment samples using FTIR spectroscopy for the first time (Thompson et al., 2004). Some important properties of the marine samples were determined using FTIR and scanning electron microscopy (SEM). It was discovered that FTIR was a useful tool for identifying and characterizing microplastics as well as differentiating between polymers. Since then, FTIR has become one of the most commonly used techniques for detecting microplastics in environmental samples (Chen et al. 2020b; Xu et al. 2019; Kedzierski et al, 2019).

Numerous studies have used FTIR to identify and quantify microplastics in water, sediment, and biota samples from various environments (Yu et al., 2019; Nandiyanto, 2019). Löder and Gerdts (2015), on their part, published an extensive review of the use of FTIR for the analysis of microplastics in environmental samples in the Journal of Marine Anthropogenic Litter.

FTIR is a non-destructive technique that is well-suited for the analysis of microplastics because it requires very small sample sizes and produces rapid results (Chen et al., 2020b). It is also a low-cost and widely available technique, making it available to researchers all over the world. The ability and ease with which FTIR can precisely determine organic compounds without being destructive distinguishes it from many other analytical methods.

A significant amount of research has been undertaken on the detection techniques utilised in the identification and quantification of microplastics in diverse environmental matrices. This review, on the other hand, contributes to current knowledge by providing concise yet relevant knowledge on these popular techniques, which are detailed in sections, as well as the benefits and drawbacks of each of the other approaches compared to FTIR spectroscopy. It is not enough to just study freshly published papers to have a deeper knowledge of these strategies. Furthermore, the assessment sheds more light on FTIR because it is the single method with the most extensive application, either alone or in combination with other techniques. The study's aims are to (1) identify the sources, types, and effects of microplastics. (2) investigate the applications of FTIR spectroscopy for Microplastic (MP) identification, (3) assess the advantages and disadvantages of detection techniques for microplastic identification and quantification, and (4) compare these feasible analytical techniques typically employed for MP identification with FTIR.

3.2. Microplastics: Sources, types, and their effect

Microplastic pollution has sparked growing global concern due to its pervasive and growing problem in marine and terrestrial environments, resulting in an explosion of studies on microplastics in recent years (Yu et al., 2019; Wang & Wang, 2018; Chen et al., 2020c; Lee & Chae, 2021; Yang et al., 2022; Lee et al., 2023; Biginagwa, 2016). MPs are small plastic particles with lengths of less than 5 mm (Baruah et al. 2022; Yang et al., 2022). They are considered a major environmental problem because they do not biodegrade and can persist for hundreds of years in the environment (Lee & Chae, 2021; Edwin, 2023; GESAMP, 2019). They can be formed through the breakdown of larger plastic items as a result of abiotic or biotic conditions such as sunshine, storms, rain, waves, and heat and by the direct release of small plastic particles, such as those found in personal care products or pellets or nurdles normally used in the production of the different kinds of plastics (Aragaw, 2021).

Microplastics can have harmful effects on wildlife, including physical harm, ingestion, and toxins transfer (Lim, 2021; Liu et al., 2019). In the environment, microplastics are a complex issue that necessitates coordinated action at all levels of society (Lee & Chae, 2021). This includes efforts to reduce the use of single-use plastics, improve waste management systems, and increase consumer awareness of the issue. In view of that research into the long-term effects of microplastics on ecosystems and human health is ongoing across the globe, which is very critical in developing effective mitigation strategies (Lee et al., 2023; Aragaw, 2021).

3.2.1. Sources of Microplastics

Microplastics come from a variety of sources, including (Fig. 3.1 and Table 3.1):

a. **Fragmentation of larger plastics:** As larger plastic items, such as bottles, bags, and packaging, break down into smaller pieces over time, they release microplastics (Primpke et al., 2020; Yang et al., 2022).

b. **Plastic pellets and pre-production plastics:** These are small plastic pellets or pre-production plastics, also known as nurdles, which are used in the production of larger plastic items and can spill or escape during transportation (Aragaw, 2021).

c. **Microbeads in personal care products:** Many personal care products, such as facial scrubs, toothpaste, and body wash, contain tiny plastic microbeads that wash down the drain and can end up in oceans and waterways (Primpke et al., 2020).

d. **Synthetic fibers from clothing:** Synthetic fabrics such as polyester and nylon shed microfibers during washing, which can enter waterways through sewage systems (Periyasamy & Tehrani-Bagha, 2022).

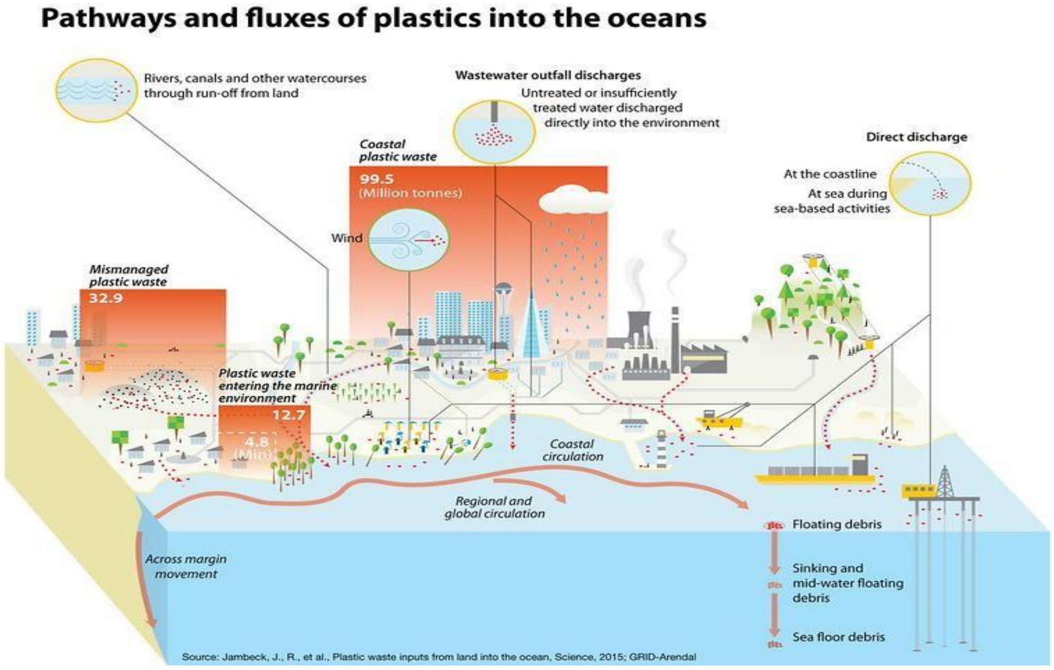
e. **Industrial processes:** Microplastics can be generated during industrial processes, such as manufacturing, transportation, and waste disposal (Ahmed et al., 2022).

f. **Wastewater Treatment Plants:** Wastewater treatment plants have now been identified as another source of microplastics (Cunsolo et al., 2021).

g. **Tire Abrasion:** Tearing and wearing of tires also serve as a source of microplastics normally found in the atmosphere (Sommer et al., 2022; Szewc et al., 2021).

h. **Paint fragments:** Road markings and some paints used to paint maritime structures and boats often break down and form microplastics (Yang et al., 2022).

i. **Foams:** PVC foams, thermal and acoustic instrument foams are also a source or microplastics (Yang et al., 2022)



Source: Jambeck, J., R., et al., Plastic waste inputs from land into the ocean, Science, 2015; GRID-Arendal

Figure 3.1: A schematic diagram illustrating sources of microplastics adapted from 'Maphoto/Riccardo Pravettoni (https://www.grida.no/resources/6921)'.

Table 3.1: Occurrence and abundance of MPs in different environmental matrices

Location	**Matrix**	**Detection Technique**	**Maximum Abundance**	**Remarks**
Poland	Air	Stereomicroscopy µATR - FTIR	Average: 10 ± 8 $m^{-2}d^{-1}$	Szewc et al. (2021)
Tunisia	Surface Water	Stereomicroscope ATR-FTIR	453.0 ± 335.2 MPs/m^3	Wakkaf et al. (2020)
China	Water Sediments	Microscope FTIR	15.88 ± 3.13 n/L 1291.33 ± 194.31 n/kg	Li et al. (2021)
Ghana	Sediment Water Bagrid Catfish Blackchinned Tilapia	Stereomicroscope	3.88 ± 1.25 per 10 g 1 ± 0.72 per 10 ml 2.88 ± 1.66 2.38 ± 2.11	Blankson et al. (2022)
South Korea	Water Sediment	ATR-FTIR	293 ± 83 to 4760 ± 5242 MPs/m^3 1970 ± 62 MPs/kg	Eo et al. (2019)
Africa	Salts	Infrared Imaging Microscope Fouriertransformed infrared (FT-IR)	^{a} 0 -1.33 ± 0.32 MPs/kg ^{b} 0 -0.33 ± 0.38 MPs/kg	Fadare et al. (2021)
Indonesia	Surface Sediments	Visual Identification	896 ± 160.28 MPs/kg	Yona et al. (2019)
Malaysia	Gray Eel-Catfish Sagor Catfish Spotted Sicklefish	Stereomicroscopy ATR-FTIR	3.92 ± 4.17 MPs/individual 2.00 ± 1.47 MPs/individual 2.00 ± 0.00 MPs/individual	Primus & Azman (2022)

Brazil	Bivalve molluscs	Optical Microscope	5.15 ± 3.80 MPs/individual	Bruzaca et al. (2022)
India	Pelagic fish	Stereomicroscope ATR-FTIR	0.07 ± 0.26 h (edible tissue) 0..53± 0.77 MPs/fish (inedible tissue)	Daniel et al. (2020)
Argentina	Surface water	Stereomicroscope Raman Microscopy	0.9 ± 0.6 MPs/m^3	Alfonso et al. (2020)
Italy	Surface water	Microscope Pyrosis-gas Chromatography/ mass spectrometry	0.9 ± 0.4 MPs/m^3	Campanale et al. (2020)
Russia	Sediment	Stereomicroscope Raman spectroscopy	863 ± 1371 MPs/kg	Chubarenko et al. (2022)

[a] = Results on salt from South Africa, [b] = Results on salts from Nigeria, Cameroun and Ghana

3.2.2. Types of Microplastic

Microplastics are classified according to their shape, colour, size, and functional groups:

a. **Shape:** Microplastics can be classified into various shapes, including fibers, fragments, and spheres. Fibers are elongated thin particles that can be released from clothing, textiles, and other materials. Fragments are irregularly shaped particles that can result from the breakdown of large plastic items. Spheres are small, spherical particles often intentionally produced for use in industrial processes.

b. **Colour:** Microplastics can be classified based on their colour. They can range from transparent to white, black, and various other colours depending on the type of plastic and the manufacturing process used to create it.

c. **Size:** Microplastics can be classified based on their size. They can range in size from less than 1µm to 5,000 µm. Microplastics smaller than 100 µm in size are often referred to as nanoplastics.

d. **Functional groups:** Microplastics can also be classified based on their functional groups, such as the type of polymer they are made of or the chemicals they contain. For example, microplastics can contain additives, such as flame retardants, plasticisers, and colourants, which can affect their physical and chemical properties.

In addition to the above classifications, microplastics are divided into primary and secondary categories (Primpke et al., 2020). Primary microplastics are purposefully produced and used for a wide range of applications, including industrial applications, personal care products, and raw materials for the manufacture of larger plastic items. Microbeads used in personal care products such as facial scrubs and toothpaste, and plastic pellets used in industrial processes, are two examples. Secondary microplastics are produced because of the breakdown and fragmentation of larger plastic items, such as plastic bags, bottles, and packaging materials. These large plastic items can degrade in the environment because of UV exposure, mechanical weathering, and chemical reactions. The resulting microplastics can then enter the environment via various routes, including land runoff, sewage effluent, and marine litter (Aragaw, 2021).

3.2.3. Effects of Microplastic

Because of their potential to harm aquatic ecosystems, wildlife, and human health, microplastics are becoming a growing environmental concern (Bhuyan, 2022; Lee & Chae, 2021; Liu et al., 2023b; Ahmed et al., 2022; Yuan et al., 2022). Although the full extent of MPs' impact on public health and aquatic ecosystems is unknown, their prevalence and negative effects on marine and freshwater biota have been widely documented (Xu et. Al. 2019; Bhuyan, 2022). Marine animals can mistake microplastics for food, causing harm or even death (Squillante et al., 2023). If consumed, they can clog the digestive tract, cause starvation, or transfer toxic chemicals into the animal's tissues, potentially causing harm to the entire food chain (Bhuyan, 2022). Microplastics can pollute rivers, lakes, and oceans, endanger aquatic life and contaminate drinking water. (Blankson et al., 2022; Ahmed et al., 2022). They do not biodegrade and can last for hundreds of years in the environment (Liu et al., 2019). They may accumulate in soils, oceans, and sediments, causing long-term environmental damage (Lwanga et al., 2022). Microplastics can enter the human food chain via contaminated seafood as well as the ingestion of air, food, and water (Edwin, 2023; Ahmed et al., 2022). They have been discovered in human tissues such as the intestine, liver, and spleen. The long-term effects of microplastic exposure on human health are unknown, but it has been linked to a variety of health issues such as inflammation, oxidative stress, cytotoxic impacts, and organ, tissue, and immune system damage (Lim, 2021; Bhuyan, 2022; Liu et al., 2019). Microplastic pollution can cause economic losses due to the decreased in productivity of aquatic systems and tourism, as well as the costs of cleaning up contaminated sites. To summarise, the presence of microplastics in the environment endangers wildlife and human health, as well as the health of our planet (Bhuyan, 2022; Lim, 2021).

3.3. Methodology

The articles used in this review were selected based on their usefulness to the study, and supporting descriptions or ideas. Search terms like “microplastic identification,” “microplastic quantification,” “FTIR,” and “analytical techniques for microplastic identification” were combined with a title search to find the best articles. Google Scholar, Scopus, PubMed, Web of Science, Pdf-drive.net, and Mendeley were databases where 500 articles and a few important books were downloaded. From the articles found, only studies and books on MP detection in environmental samples using FTIR (or other analytical techniques) were kept. The review of the literature was carried out until 129 research papers and books relevant to the scope of the study were discovered and used. Articles were accepted if they were published in English and described the concept of FTIR and other analytical techniques for microplastic identification and quantification. Because the goal was to find the best peer-reviewed articles and books, there was no year of publication restriction; however, the majority of the articles and books consulted were recent.

3.4. Fourier Transform Infrared Spectroscopy (FTIR)

Microplastics are commonly identified and characterised using FTIR. This technique measures a sample's absorption or transmission of infrared radiation, providing information about the sample's chemical composition and type of microplastics present. Earlier studies by Fadlelmoula et al. (2022) and Vogt et al. (2019) validate this method. The FTIR technique uses infrared radiation to analyze organic, polymeric, and inorganic materials. The instrument sends radiation through a sample, which absorbs some of the radiation, converting it into molecular energy. The resulting signal at the detector produces a spectrum that represents the sample's molecular fingerprint. FTIR analysis can identify chemicals by their unique spectral fingerprint, making it a valuable tool for chemical identification.

Their strong abilities have led to their use in a variety of fields, particularly material science and engineering. FTIR spectroscopy is a well-established technique for quality control in material analysis and is frequently used as the first step in the material analysis process.

FTIR has gained importance due to environmental concerns over microplastics. Its advantage includes analyzing a sample's chemical composition without harming it, enabling multiple analyses (Vogt et al., 2019; Thomas et al., 2017.

FTIR has limitations in identifying microplastics, mixtures of different plastic types, and very small microplastics. It requires expertise and proper equipment maintenance. MicroFTIR was developed to identify smaller particles down to 20 µm.

3.4.1. Analytical Instruments for FTIR Analysis Several

machines are used for FTIR analysis:

1. Fourier Transform Infrared Spectrometer (FTIR): This is the primary instrument used for FTIR analysis, and it produces an infrared spectrum of the sample by measuring the intensity of infrared light that passes through or is reflected off the sample (Wang & Wang, 2018; Smith, 2014).
2. Attenuated Total Reflectance (ATR) Accessory: When connected to an FTIR spectrometer, this attachment enables for the examination of solid and liquid materials without the requirement for sample preparation (Xu et al., 2019; Kedzierski et al., 2019; Primpke et al., 2018; GESAMP, 2019; Shim et al., 2017).

3. Infrared microscopy: A micro-FTIR instrument is a combination of an FTIR spectrometer and a microscope. This enables the examination of tiny plastics in a sample, such as microplastics. The infrared beam is focused on the particle of interest using a microscope, and the resultant spectrum is measured using an FTIR spectrometer. To detect and quantify microplastics in water, soil, and biological samples, microscope-FTIR equipment is often utilised (Löder & Gerdts, 2015).
4. FTIR Imaging: FTIRI devices employ an array detector to create a two-dimensional image of a material,

with each pixel representing a single spectrum. This enables the detection and mapping of microplastics in a sample, as well as the assessment of microplastic size and distribution. FTIRI devices are frequently employed to investigate complicated environmental materials, such as sediments or soil, where microplastics might exist in low quantities (Watteau et al., 2018).

Portable FTIR: These are compact, portable instruments that may be used in the field to identify and quantify microplastics in real-time. These tools are often less sensitive than laboratory-based equipment, but they are effective for screening environmental samples and finding microplastic contamination hotspots (Asamoah et al., 2021).

5. Transmission FTIR analysis: This form of FTIR analysis detects the infrared radiation that goes through a material and is often used for thin film and coating examination (Primpke et al., 2020).

The requirements of the analysis and the kind of material being looked at dictate the machine to be utilised. Every machine has a unique collection of functions and characteristics.

3.4.2. Procedures and processes for undertaking FTIR analysis

A meticulous approach to sample preparation, spectrum acquisition, interpretation, and data reporting is necessary for the complex process of FTIR analysis (Liu et al., 2022a; Liu et al., 2022b; Smith, 2011; Smith, 2014). However, it is a very useful method for identifying and characterizing a material's chemical makeup, which makes it a widely employed analytical tool across several industries (Shim et al., 2017; Chen et al., 2020c).

The following are the steps needed to evaluate a material using FTIR (Smith, 2014; Larkin, 2011):

The sample needs to be processed before using FTIR to examine microplastics (Süssmann et al., 2021). The substance has to be in a form that makes FTIR spectroscopy possible (Primpke et al., 2018; Zakeri et al., 2020). The sample can be combined with the proper solvent or matrix to dissolve, mix, or grind it. Next, the FTIR device is configured. This procedure entails calibrating the detector, choosing an appropriate beam splitter, and aligning the optics. To achieve accurate measurements, the instrument has to be calibrated on a regular basis. A background measurement is made in order to account for any absorption by the surrounding environment prior to analyzing the sample.

Usually, a tiny quantity of material is obtained and put on a microscope slide to start the sample examination. 2021; Lee & Chae. After that, the slide is put through analysis using an FTIR device or apparatus. As seen in Figure 3.2, the FTIR instrument usually plots the strength of the absorbed or transmitted infrared radiation as a function of frequency to create the sample's spectrum.

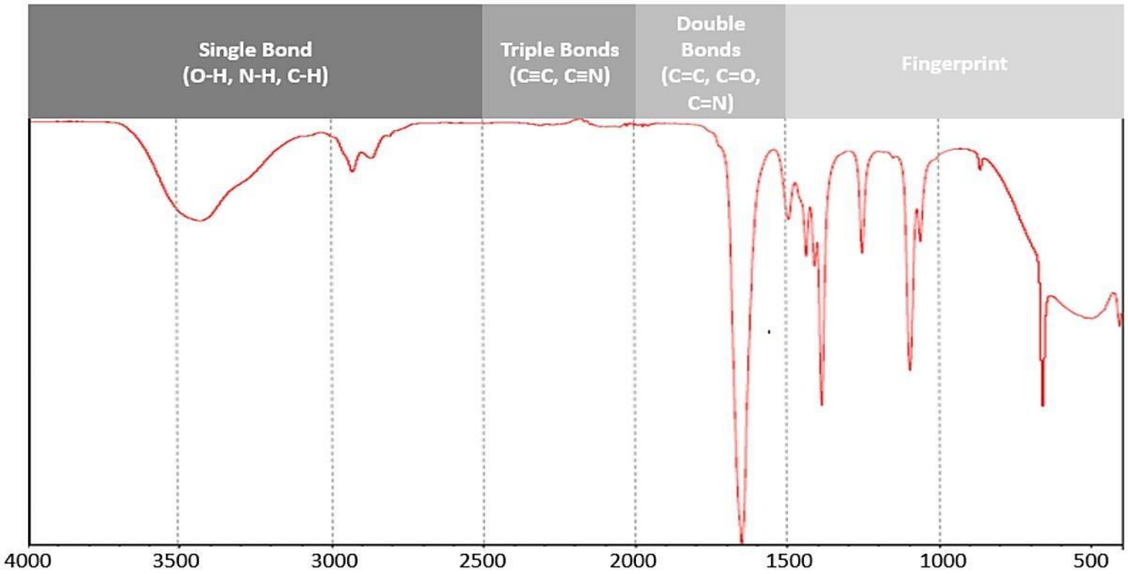


Figure 3.2: FTIR spectra of plastics Adopted from Coates (2000) and Nandiyanto (2019)

The spectrum has to be processed and analyzed when it is acquired. This means finding the peaks and bands in the spectrum and removing any baseline drift or noise. The spectrum is compared to a library of known spectra to identify the kind of plastic and to ascertain the chemical components of the sample (Nandiyanto, 2019; Chen et al. 2020b). Databases and a variety of software tools are used to make this feasible (Dong et al. 2023). In addition, various characteristics of plastic, such its molecular structure (i.e., functional groups and chemical bonds of the sample in addition to its overall chemical structure) and degree of degradation, may be ascertained using the spectrum (Weisser et al., 2022; Primpke et al., 2020). This data may be used to determine the sample's identity, assess its purity, and find any contaminants or impurities. In the end, the results of FTIR analyses are frequently presented in a way that is suitable for implementation. This might yield a quantitative measurement of the analyte concentration or a qualitative determination of the sample's makeup.

3.4.3. FTIR Advantages and Drawbacks

FTIR is preferred over other chemical analysis methods for a number of reasons (Luo et al., 2022). An efficient technique for figuring out the chemical makeup of unknown materials is FTIR spectroscopy. It is appropriate for a variety of applications due to its broad-spectrum range, which includes a wide range of chemical functional groups (Yu et al., 2019; Chen et al. 2020b). FTIR analysis is the most dependable method for figuring out a sample's chemical makeup when compared to other analytical techniques (HidalgoRuz et al., 2012). This technique works well with small samples and doesn't require any sample preparation. Since the process is non-destructive, the sample is not harmed while it is being analyzed (Larkin, 2011). When working with rare or valuable samples, this is crucial (Smith, 2014).

A sample's concentration of a particular chemical can be determined quantitatively using FTIR. Liquids, solids, and gases are among the materials they may be used to evaluate (Zakeri et al. 2020). Investigating complex mixtures, such as polymers or biological materials, may also be done using it. FTIR is a very sensitive technique that can find minute concentrations of compounds (Schwaferts et al., 2019). It may also be applied to the investigation of complex polymer and biological material combinations. It is also a fastgenerating tool, which makes it perfect for high-throughput screening. Due to its generally lower cost compared to some analytical techniques, FTIR analysis is an attractive substitute for a variety of applications (Schwaferts et al., 2019). It is also a flexible and frequently used analytical method with diverse applications in chemical analysis.

Prior to selecting FTIR over alternative analytical techniques, the specific requirements of the analysis and the method's inherent limitations must be considered (Luo et al., 2022). Obtaining precise and consistent results requires careful sample preparation. Furthermore, the analysis can be compromised by environmental interference, such as water vapour and atmospheric gases. Interpreting FTIR spectra is a complex process that demands specialised software and operator expertise. While highly sensitive, FTIR has detection limits that may be insufficient for trace concentrations of certain analytes (Li et al., 2017). Although often less expensive than other instrumentation, the initial cost of an FTIR system can be significant, with expenses increasing for necessary accessories and analytical software (Smith, 2014).

3.4.4. Research and development efforts to improve FTIR methods for microplastic analysis

Microplastics may be identified and measured using FTIR, a powerful analytical method (Fadlelmoula et al., 2022; Luo et al., 2022). According to Renner et al. (2019) and Cunsolo et al. (2021), however, ongoing research and development efforts are being made to increase its sensitivity, accuracy, and speed. Listed below are a number of these initiatives:

- One major obstacle to FTIR analysis of microplastics is the difficult and timeconsuming sample preparation process (Lee & Chae, 2021). To handle numerous samples quickly and accurately, researchers are working to create automated sample preparation processes (Renner et al., 2019).

- Moreover, a great deal of work has gone into making spectrum libraries better. As stated by Renner and colleagues in 2017 and 2019. The identification and quantification of microplastics need a sizable spectrum library. Because of this, researchers are trying to create a spectrum library that is more extensive and has a wider variety of polymer kinds, colours, and degradation products (Grant-Peters & associates, 2022).
- According to Dashlahra et al. (2010), the FTIR sensitivity is insufficient for identifying microplastics smaller than 20 µm in environmental samples including several microplastic kinds. By improving the signal-to-noise ratio (by increasing the number of scans or the intensity of the infrared beams), creating new sampling techniques (by increasing the analyte concentration in the sample and enhancing the detection limit), and fine-tuning instrument settings (by tracing the fine points of the curve and extracting the best spectral fingerprints of the sample during analysis), researchers are attempting to increase FTIR sensitivity (Hermann et al., 2017; Barra et al., 2021; Deshlahra et al., 2010).
- To effectively recover microplastics from a variety of intricate environmental matrices, researchers are also creating innovative extraction techniques (Cunsolo et al., 2021; Crichton et al., 2017; Fadare et al., 2021; Daniel et al., 2020). Since microplastics are frequently discovered embedded in these matrices, extraction is a challenging procedure (Bai et al., 2022; Cunsolo et al., 2021). The potential of artificial intelligence (AI) and machine learning (ML) to support the identification

and measurement of microplastics from FTIR spectra has also been investigated (Grant-Peters et al., 2022; Vogt et al., 2019). Kedzierski et al. (2019) used FTIRATR spectra to automatically determine the kind of microplastic through the development of a unique machine-learning technique called k-nearest neighbour classification. In eradicating microplastic contamination from biological ecosystems by accurately detecting it and giving an image of how they are dispersed, Machine learning (ML) is being employed. According to Singh et al., (2023), ML could be one of the best solutions for accurately detecting microplastic particles.

- Through research and development, data mining techniques and chemometric analysis are being used for spectra data processing (Neo et al., 2022; Renner et al., 2017; Hufnagl et al., 2021). It has been employed to process and extract relevant information from FTIR spectra in the areas of noise reduction, baseline correction, and peak detection to improve the quality of data (Rohman et al., 2020). Additionally, researchers are exploring the use of deep learning techniques, such as convolutional neural networks (CNNs), for image-based FTIR microplastic analysis to improve accuracy in identifying complex microplastic structures (Liu et al., 2023c). Chemometric analysis such as the application of multivariate data analysis methods like PCA (Principal Component Analysis) and PLS (Partial Least Squares) to model and interpret FTIR data is being tried to aid in better quantification and classification of microplastics (Asamoah et al., 2021; Bara et al. 2021; Malaspina et al., 2018). Tan et al. (2023) in their study proposed a FTIR spectroscopy combing with quaternion parallel feature extraction methodology for the first time to address the qualitative and quantitative analysis of microplastics.

These are a few of the most important studies that have been conducted to solve issues with the technique's sensitivity, speed, and accuracy in order to gain a better understanding of the effects of microplastics on the environment.

3.5. Other Analytical Techniques for Microplastics Identifications

There are equally important analytical techniques for studying microplastics that can be used in addition to or instead of FTIR. These techniques have their pros and cons similar to that of FTIR and are employed either alone or in addition to the FTIR technique depending on their strengths and weaknesses. The appropriate analytical technique to adopt is determined by the specific needs of the study, as well as the type of material being investigated. For instance, the work by Squillante et al. (2023) employed both Gas Chromatography-Mass Spectrometry (GC-MS), and FTIR. While the GC-MS was employed for the phthalic acid esters (PAE) analysis, the FTIR on the other side was used to detect MPs in fish samples.

Some of the most essential and extensively utilised techniques available for microplastics quantification and to identification are as discussed below:

3.5.1. Optical techniques

Optical methods are commonly used for microplastic detection due to their ability to provide rapid, non-destructive, and high-resolution particle examination (Blankson et al., 2022; Wang & Wang, 2018; Haris et al., 2020). According to a report by GESAMP (2019) and Haris et al. (2020), the visual examination is a must regardless of the sample processing type that is employed in the microplastic analysis. Although tedious, it is worth the time spent at this stage (GESAMP, 2019). Zakeri et al. (2023) employed a stereomicroscope for the initial observations even before employing µFTIR for polymeric characterization of the microplastics. In the case of Akhbarizadeh et al. (2020), the researchers after employing the KRÜSS binocular microscope, went ahead used fluorescence microscopy, MicroRaman Spectroscopy, and Scanning Electron Microscope (SEM)-Energy Dispersive X-ray (EDX) techniques. Daniel et al. (2020) likewise used the Motic SMZ-168 Stereo microscope for initial identification and counting or classification of the microplastics and then followed that with the ATR- FTIR.

Visual Examination usually involves the use of light to observe and analyze the properties of microplastics, such as their size, shape, colour, and texture (Kotar et al., 2022; Yona et al., 2019). One of the simplest and widely used methods for identifying microplastics is visual identification, which can be done with the naked eye or with a microscope (Thaiba et al., 2023; Prata et al., 2019b). However, microplastics can be examined and researched using a variety of microscopes, including stereomicroscopes and compound microscopes (Zakeri et al., 2020). Particles are grouped according to their morphology (fragment, pellet, fiber/line, film, and foam) under this technique, and their sizes are measured along their longest edge (GESAMP, 2019).

Optical techniques offer various benefits, which is why they are employed in practically all investigations on microplastic detection and quantification. In comparison to FTIR, the procedure is quite simple and does not need the analysis to be performed by a trained operator. It produces quick results and is hence appropriate for high-volume samples (Lusher et al., 2017). This technology efficiently extracts useful information on the sources and types of microplastics based on size, shape, and color.

Optical techniques, like the FTIR technique, are non-destructive, allowing for further analysis or repetition of analysis. Furthermore, because optical techniques are nondestructive, they can be combined with any other technique to get a better identification and classification of the microplastic (Ruangpanupan et al., 2022).

The approach, however, falls short of a thorough microplastic examination in comparison to FTIR. The approach is inapplicable at extremely small sample sizes (less than 100 µm) but FTIR is employed for samples of sizes as small as 20 µm (Shim et al., 2017). It may be unable to identify very minute or transparent microplastics using only optical techniques (Van Tran et al., 2023). It becomes exceedingly difficult to distinguish between particle contaminants and the materials being tested when using optical techniques but FTIR techniques work perfectly in such as analysis (Dong et al., 2023). Furthermore, unlike FTIR, the approach only offers morphological information and cannot detect the chemical makeup of distinct microplastics.

The optical approach has a significant problem in that the accuracy of the results is reliant on the examiner, sample matrix, shape and size, and inspection microscope, unlike the stereoscopic approaches such as FTIR (Dong et al, 2023; Van Tran et al. 2023). As a result, it is usually used in conjunction with electronic microscopes, spectroscopic equipment, or other analytical techniques to confirm the identity of suspected microplastics, especially for smaller particles (Dong et al, 2023; Wang & Wang, 2018). Nonetheless, some researchers only employ optical microscopy in quantifying microplastics without necessarily combining it with other techniques (Bruzaca et al., 2022).

3.5.2. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) has also been used widely in numerous research fields since the inception of electron microscopes in the 1930s and has become one of the most useful analytical tools employed in microplastic identification and quantification (Huang et al., 2023; Primpke et al., 2020; Fadare et al., 2021; Akhbarizadeh et al., 2020). The technique is a microscopic technique which is able to provide information about the morphological surface structure of MPs, generating high-resolution images of the surface state (Mariano et al., 2021; Fadare et al., 2021; Thaiba et al., 2023; Prata et al., 2019b; Yuan et al., 2022; Wang & Wang, 2018).

According to Sarkar et al. (2023) and Vitali et al. (2022), SEM helps to observe tiny particles on the surface of samples up to sizes of nanometers scale that an optical microscope may miss since the wavelength is much below that of visible light (200 – 400 nm). Moreover, using SEM with energy-dispersive X-ray spectroscopy (EDS), which has been the usual phenomenon, the technique can offer information on the elemental composition of the microplastic (Huang et al., 2023; Mariano et al., 2021; Blair et al., 2019; GESAMP, 2019; Akhbarizadeh et al., 2020). Akhbarizadeh et al. (2020) in their work employed the SEM with EDX and due to the powerful nature of theotentiale in identifying tiny particles, trace elements (i.e., Ti, Cu, Al) were even found in the canned tuna and mackerel fish samples analyzed. Similarly, Fadere et al. (2021) used SEM with EDX for the morphological characterization of the particles and this was done after the residues on the filter papers were visually inspected with the aid of an optical microscope and the polymer characterization was also been carried out using Infrared Imaging Microscope Fourier-transformed infrared (FTIR) spectrometry.

SEM works by scanning a focused beam of electrons across the surface of a sample which results in the formation of backscattered electrons (BSE) (elastic interactions), secondary electrons (SE) (inelastic interactions), and characteristic X-rays (Primpke et al., 2020; Chen et al., 2020c). The BSE and SE released from the sample surface are collected with the detectors and converted into signals (Vitali, 2022). The signals lead to the production of high-resolution images (Li et al., 2017). These images offer extensive information on the size, shape, surface roughness, and elemental content of individual particles. To prepare a sample for SEM examination, the microplastics must be removed and purified from the sample matrix (e.g., sediment, water, or biological tissue). This can be accomplished using several procedures such as filtering, digesting, and density separation (Abbasi et al., 2018; Süssmann et al. 2021; Zakeri et al., 2020). After extraction, the microplastics can be put on a sample holder and covered with conductive carbon tape as was used in Akhbarizadeh et al. (2020), and Jozanikohan & Abarghooei (2022) or stain coated for the analysis to be executed.

SEM is a potent method for the identification and characterization of microplastics in general, and it can be used in tandem with other analytical techniques most especially FTIR as was captured in studies by Thompson et al. (2004) and Blair et al. (2019) to give a more thorough knowledge of microplastic contamination in the environment (Veerasingam et al., 2020a; Thomas et al., 2017; Winkler et al., 2019).

The method is normally employed for the further surface characterization and elemental analysis of plastics such as polyvinyl chloride (PVC), especially when studying weathering or chemical damage to the surface (GESAMP, 2019; Chen et al., 2020c; Winkler et al., 2019).

SEM is more sophisticated than optical techniques because it offers exact size and shape information of the microplastics being investigated, allowing researchers to properly detect and categorise microplastics, particularly in the presence of impurities (Shim et al., 2017; Wagner et al., 2017). The high-resolution imaging provides for precise inspection of microplastic shape and surface characteristics of particles as small as 1 nm (Shim et al., 2017; Soursou et al., 2023), which FTIR Spectroscopy cannot observe. The approach allows the researcher to see the physical properties of the sample, such as particle size, shape, and distribution (GESAMP, 2019). The crystalline phases present in the sample may be detected using Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD), offering information into the arrangement of atoms that FTIR spectroscopy cannot perceive.

However, one major disadvantage of SEM over FTIR is that the sample to be analyzed must be conductive, whereas most microplastics are non-conductive, necessitating staincoating with metal or carbon via either sputter coating or vacuum deposition (Blair et al., 2019; Thaiba et al., 2023). As a result, pretreatment processes are extremely complicated, resulting in a technique that is expensive, time-consuming, and inefficient (Van Tran et al. 2023; Huang et al., 2023; Thaiba et al., 2023; GESAMP, 2019). Nonconducting materials, however, can be scanned without coating using specialist SEM devices such as Environmental SEM (ESEM) or field emission guns (FEG). SEM, like

FTIR, often requires competent individuals to run the instrument and interpret the data. Although the approach gives chemical information when combined with EDS, it is restricted in comparison to FTIR in that it lacks the capacity to detect individual polymers or additives present in microplastics.

Although SEM is useful for high-resolution imaging and comprehensive morphological information of the material under research, its inability to distinguish the type of polymer that the microplastic is comprised of, like FTIR can, makes it impossible to employ alone especially when you are undertaking a comprehensive analysis (Van Tran et al., 2023). As a result, it is frequently used in conjunction with other procedures to obtain precise information on microplastics.

3.5.3. X-ray Fluorescence (XRF)

The elemental composition of a sample can be determined using X-ray fluorescence (XRF), a non-destructive, easy, and fast analytical method (Jozanikohan & Abarghooei, 2022; Sonbhadra & Pandey, 2022; Yadav et al., 2023; Prata et al., 2019b). XRF has been employed extensively as a tool for detecting microplastics in environmental samples for some years now (Zhang et al., 2021; Guerra et al. 2014; Chaqmaqchee et al., 2017; Veerasingam et al., 2020b). Turner (2017) and Massos & Turner (2017) examined the elemental compositions of polymers using a portable X-ray fluorescence spectrometer.

The technique works by striking the surface of microplastic with a high-energy X-ray beam (Sonbhadra & Pandey, 2022; Chaqmaqchee et al., 2017; Jozanikohan & Abarghooei, 2022). This, in turn, emits lower energy X-rays, a phenomenon known as ‘fluorescence’ (“X-ray Fluorescence (XRF) Analysis of Porcelain: Background Paper,” 2017). Each chemical element emits fluorescent X-rays with distinct energies. The emitted X-rays are shown as a spectrum with varied height peaks at various energies. The energy of a peak identifies the chemical element responsible for it, and the height of a peak is generally related to the amount of that element in the sample ("Hand-held X-ray Fluorescence Spectrometry," 2019). The identified elements are then measured and quantified using the software. To calibrate the method or to check for bias in the findings, reference materials are always employed ("X-ray Fluorescence (XRF) Analysis of Porcelain: Background Paper," 2017).

Energy-dispersive (EDXRF) and wavelength-dispersive (WDXRF) XRF spectrometers are the two types of commonly available XRF devices (Yadav et al., 2023; Prata et al., 2019b). Although their basic principles are similar, EDXRF and WDXRF differ in the approach employed to quantify the distinctive radiation and intensities released by fluorescent X-ray photons (Primpke et al., 2020; Turner, 2017; Yadav et al., 2023). WDXRF equipment measures the wavelengths of X-ray photons, which are inversely related to their energy, whereas EDXRF instruments directly measure the energy of fluorescent X-ray photons ("X-ray Fluorescence (XRF) Analysis of Porcelain: Background Paper," 2017). Chaqmaqchee et al., (2017) demonstrated the application of EDXRF for plastic identification when the researchers used to technique to determine the chemical composition of different plastic materials.

X-ray fluorescence (XRF) is a promising approach for detecting microplastics in environmental samples (Yadav et al., 2023; Sonbhadra & Pandey, 2022). It offers a relatively quick result than FTIR spectroscopy. It also has the benefit of being nondestructive as in the case of FTIR, but its capacity to identify just the elemental makeup of the sample limits its ability to discern between different types of plastics and additive dyes such as dyes and plasticisers (Fu et al., 2020).

3.5.4. Raman Spectroscopy

Raman spectroscopy is a type of vibrational spectroscopy that is used to investigate the chemical and physical characteristics of materials (Asamoah et al., 2021; Sobhani et al., 2019; Sobhani et al., 2020; Dong et al., 2020; Li et al., 2017; Guerra et al. 2014). It is based on the Raman effect, which is the scattering of light by a material that causes the wavelength of the scattered photons to change (Sobhani et al., 2020). A laser is aimed at a sample in Raman Spectroscopy, and the scattered light is collected and evaluated (Larkin, 2011; Luo et al., 2022). When incoming laser light interacts with chemical bonds in a sample, they vibrate, generating the Raman effect (Dong et al., 2020). The information included in the dispersed light emitted by the sample regarding these vibrations can be utilised to identify the chemical makeup and molecular structure of the substance.

Raman spectroscopy can be used to investigate a variety of materials, including solids, liquids, and gases (Huang et al., 2023; Schwaferts et al., 2019). It is particularly useful for studying substances that are difficult to assess using traditional methods, such as polymers, ceramics, and biological materials (Dong et al., 2020; Schymanski et al., 2018). Raman spectroscopy can also be used to investigate the crystalline structure of a material and to detect contaminants in samples (Bauer et al., 2022; Thomas et al., 2017).

Raman spectroscopy is a powerful analytical technique that has recently gained popularity in the detection of microplastics (Wang & Wang, 2018, Schymanski et al., 2018; Vinay

Kumar et al., 2021). Microplastics, which are composed of various polymers, have distinct Raman spectra that can be used to determine their chemical composition. Each polymer has a unique Raman spectrum, allowing for the identification and differentiation of various types of microplastics (Huang et al., 2023).

Furthermore, the Raman spectrum can reveal information about the size and structure of the microplastic, as well as any additives or impurities that may be present (Böke et al., 2022). The excellent sensitivity and specificity of Raman spectroscopy for microplastic detection is a significant advantage. It can detect microplastics even at very low concentrations, making it an invaluable tool for environmental monitoring and research.

Raman spectroscopy is a non-destructive technique (Larkin, 2011). Because only a small amount of light is required to evaluate a sample, the method is ideal for studying fragile or valuable materials. Raman Spectroscopy is also quick and easy to use, which makes it a popular choice for a wide range of applications in research, industry, and forensics (Alfonso et al., 2020).

However, there are several disadvantages to using Raman spectroscopy to detect microplastics (Liu et al., 2022b). One limitation is that reliable results require a clean surface, which may be difficult for microplastics present in environmental samples that are coated in organic or inorganic debris (Van Tran et al., 2023; Huang et al, 2023). Furthermore, the method cannot be used to identify extremely small MPs because the signal may be too faint to detect. It is for this reason that micro-Raman spectroscopy has been developed to aid in identifying extremely small MPs. A typical example is the study by Vinay Kumar et al. (2021) which employed micro-FTIR for the identification of MPs in some commercially important mussels and further utilised the micro-Raman to identify the MPs < 50 µm. This combination helped to reliably detect and characterise MPs down to a size of 3 µm.

Raman spectroscopy in general is a promising technique for identifying microplastics, and its use is likely to increase as awareness of microplastic pollution grows (Löder & Gerdts, 2015).

In contrast to FTIR, which measures infrared light absorption, Raman spectroscopy detects the scattering of visible or near-infrared light, resulting in a unique spectroscopic fingerprint (Dong et al., 2023). This allows the method to detect chemical groups that FTIR could miss, making it useful for distinguishing between different polymers and additives. It is also less sensitive to water and moisture than FTIR, making it appropriate for studying materials with a higher water content. When compared to FTIR, it requires less sample preparation, making it a more straightforward and efficient method.

Despite the advantages of Raman over FTIR, Raman spectroscopy is particularly sensitive to the stabiliser and pigment compounds in microplastics, which impact polymer identification (GESAMP, 2019). It is weaker than FTIR due to its susceptibility to fluorescence interference and the possibility of sample heating (Singh et al., 2023; Löder & Gerdts, 2015).

Furthermore, Raman spectroscopy has a limited penetration depth, commonly measured in micrometers (Lusher et al., 2017). This implies it may not be suited for assessing materials with significant thickness or researching the composition of materials with bulk samples.

FTIR spectra are significantly simpler to interpret than Raman spectra, especially when many vibrational modes overlap, making it difficult to identify individual functional groups or materials.

Unlike microscopy, which is faster than FTIR, Raman spectroscopy takes longer acquisition periods, especially when dealing with weak Raman signals (Singh et al., 2023). Finally, microplastics with a greater number of hydrogen bonds are less sensitive to Raman than they are to FTIR.

3.5.5. Dynamic Light Scattering (DLS)

The method of Dynamic Light Scattering (DLS) has also been used in identifying microplastics (Chicea, 2020; Caputo et al., 2021; Primpke et al., 2020; Huang et al., 2023; Fu et al., 2020). Although it is used for microplastic identification, it is known to have great potential in the identification of nanoplastics (Haung et al. 2023). It is a non-invasive optical approach that uses Brownian motion to determine the size distribution of particles in a sample (Fu et al., 2020; Schwaferts et al., 2019).

Under this technique, a laser is sent through particles in solution, and the scattered light is detected. The detected particles induce a shift in light frequency. The shift results in temporal fluctuations which contain information on the particle shape and size distribution (Fu et al., 2020). However, larger particles in polydisperse samples conceal small ones due to variations in scattering behaviour between particles of various sizes, resulting in an inaccurate size distribution (Primpke et al., 2020). Therefore, DLS is suitable for samples with average sizes of particles (Fu et al., 2020).

The technique is specially known for distinguishing between spherical microplastics, such as microbeads, and irregularly shaped microplastics, such as fragments of more oversized plastic products. Additionally, it is also used to detect the presence of microplastics in a sample at low quantities (Primpke et al., 2020). This is because DLS is a very sensitive technology capable of detecting even minor changes in the size distribution of particles in a sample (Thaiba et al., 2023; Pecora, 2000). Generally, due to its sensitivity, noninvasiveness, and capacity to discriminate between different types of particles depending on size and shape, DLS is an effective approach for identifying microplastics (Caputo et al., 2021).

Unlike FTIR, DLS needs minimum sample preparation, which saves time and effort for detecting microplastics. Furthermore, many microplastic investigations simply require particle sizes and concentration, and DLS performs better than FTIR in such analyses since it does not require any chemical analysis or the identification of specific polymer types. It is extremely useful for determining the hydrodynamic diameter of particles in a suspension, which is necessary for assessing the size range of microplastics in environmental samples. DLS might be used to offer real-time data on particle size or aggregation dynamics in the investigation of microplastics under diverse environmental settings.

Although DLS has some benefits over FTIR, it is nevertheless restricted in terms of delivering chemical information on microplastics. DLS cannot detect the kind of polymers in environmental samples, however FTIR can. DLS is also most effective when studying particles in suspensions or colloidal systems. It may not be suited for analyzing individual microplastics, as FTIR is. FTIR outperforms DLS for opaque or highly colored microplastics because DLS is confined to transparent and semi-transparent particles. Finally, DLS is known to struggle with producing correct size distributions for samples with a broad range of particle sizes or extremely heterogeneous mixes.

3.5.6. Laser-Induced Breakdown Spectroscopy (LIBS)

LIBS (Laser-Induced Breakdown Spectroscopy) is a microplastic identification tool that does not feature in most of the reviews on analytical techniques (Sommer et al., 2022; Gondal & Siddiqui, 2007; Chen, et al., 2020d; Giugliano et al., 2022; Neo et al., 2022). The LIBS approach entails vaporizing a tiny sample of the material to be studied with a high-energy laser and then analyzing the ensuing plasma emission spectrum to determine the elemental makeup of the substance (Chen et al., 2020c; Chen et al., 2020d).

To use LIBS to identify microplastics, the sample is first collected and then cleaned and dried (Brunnbauer et al., 2020; Brunnbauer, Larisegger, et al., 2020; Gondal & Siddiqui, 2007). After that, the sample is put on a target holder in front of the laser beam (Giugliano et al., 2022). The laser is focused on a tiny area of the sample, causing asmall amount of material to be evaporated and ionised, resulting in the formation of plasma (Brunnbauer et al., 2022; Brunnbauer, Larisegger, et al., 2020). A spectrometer captures and analyzes the light spectrum emitted by the plasma. The elemental composition of the microplastic can be detected by comparing the spectrum obtained from the microplastic sample to a known reference spectrum.

The LIBS approach can be used to detect a wide range of plastic types, including polyethylene, polypropylene, polystyrene, and others (Sommer et al., 2022; Brunnbauer et al., 2022; Brunnbauer, Larisegger, et al., 2020). One advantage of the LIBS approach for microplastic detection is its ability to examine materials swiftly and non-destructively (Zeng et al., 2021). Moreover, the approach can be utilised to assess very tiny samples, making it ideal for microplastic examination. However, the procedure does need specific equipment and knowledge, which can restrict its use.

The LIBS approach though newer than Raman and FTIR, is a potential tool for microplastic detection, and its continuing development and implementation can contribute to the knowledge and mitigation of microplastic contamination since it has no drawback of insensitivity with some specific chemical bonds (Neo et al., 2022). Brunnbauer, Larisegger, et al. (2020) in their quest to classify polymers utilised the LIBS technique and it worked out perfectly as was required.

Compared to FTIR, LIBS is far better in providing very rapid results without necessarily going through extensive sample preparation. Due to its ability to give results in short time, it is mostly employed in determining whether there is a microplastic in an environmental sample or specific areas within a sample. In remote or challenging environment, LIBS is employed over FTIR for in situ analysis of microplastics.

Similar to most of the techniques discussed earlier in this study, LIBS also do not provide detailed information about the chemical structure of microplastics or does not determine the kind of polymer the microplastic was made of. Even additives that are easily detected by FTIR in microplastics analysis, LIBS do not provide accurate information on that. Due to this limitation, LIBS is always use in addition to other analytical techniques to provide extensive quantitative and qualitative analysis of microplastics.

3.5.7. Pyrolysis Gas Chromatography/Mass Spectrometry (Py-GC-MS)

Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC-MS) is a microplastic detection technique that has been used to identify and quantify microplastics in various samples (Cho et al., 2023; Picó & Barceló, 2020; Yu et al., 2019; Wang & Wang, 2018; Watteau et al., 2018; Fries et al., 2013; Shim et al., 2017; Hermabessier et al., 2018). Pyrolysis involves the reduction of a substance to its constituent parts by heating it to high temperatures in the absence of oxygen. (Liu et al., 2021; Watteau et al., 2018).

The technique requires little sample preparation but separates and analyses the microplastic pyrolysis products using gas chromatography and mass spectrometry. (Cho et al., 2023; Hermabessier et al., 2018). It can detect the type of plastic used to create microplastics. (Primpke et al., 2020). This is because different types of plastic have different chemical compositions, and pyrolysis breaks the plastic down into its essential chemical components (Picó & Barceló, 2020). According to Becker et al. (2020), the technique can be used to identify the exact chemical components present as well as the type of plastic from which the microplastic is formed by examining the pyrolysis products using GC-MS.

Py-GC-MS is a highly sensitive technology that can detect even trace amounts of microplastics in a sample, making it useful for environmental monitoring and research. (Liu et al., 2022b; Harata et al., 2020). It can also detect the presence of additives and impurities in the plastic, such as plasticisers and dyes, which can provide important information about the potential environmental impact of the microplastic (Li et al., 2017; Watteau et al., 2018; Becker et al., 2020; Löder & Gerdts, 2015). Even though the technique is said to be more sensitive than other methods and less affected by sample impurities and interferences, Picó and Barceló (2020) report that some samples have significant interferences due to organic matter.

Py-GC-MS is an effective method for identifying microplastics because it provides detailed information about the plastic's composition and can be used to influence environmental laws and regulations (Fries et al., 2013; Watteau et al., 2018). Harata et al. (2020) confirmed the effectiveness of this technique when the researchers used Py-GC for the identification and quantification of microplastics. The researchers concluded that Py-GC was a promising technique for the characterization of complex mixtures of environmental MPs. However, one significant limitation of the technique is that it is destructive, unlike FTIR. (Yuan et al., 2022). This makes it difficult to replicate an analysis or prevents additional microplastic sample analysis (Picó & Barceló, 2020; GESAMP, 2019).

Py-GC-MS, like FTIR, offers rich information about the kinds of polymers present, allowing for exact characterization (Lusher et al., 2017; Soursou et al., 2023). However, the Py-GS-MS goes a step further by identifying monomers and chemical bonds in the microplastics' molecular structure (Squillante et al., 2023). This level of specificity aids in comprehending the origin and degradation of microplastics. It can identify tiny quantities of chemical compounds inside microplastics even at low concentrations. Because of its sensitivity, the method is less vulnerable to sample matrix interference than FTIR, resulting in valid findings even in complicated sample matrices. It is also not suitable for identifying a large number of samples (Van Tran et al. 2023). Unlike FTIR, this approach necessitates a highly skilled operator as well as considerable time and effort for instrument runs and data processing (GESAMP, 2019). However, as Hermabessier et al. (2018) showed, the approach may be used to supplement the results of FTIR and Raman techniques.

Table 3.2 provides an overview of the strengths and drawbacks of all the analytical approaches addressed in the paper.

Table 3.2: Summary of the nature of all analytical techniques for identification and quantification of microplastics in the environment discussed above

Technique	**Principle**	**Strength**	**Limitation**	**Remarks**
Optical Technique	These techniques frequently involve the use of light to view and analyze microplastic features such as size, shape, colour, and texture.	Quick, non-destructive, and high-resolution analysis of particles, and suitable technique for high-volume samples.	The examiner's subjectivity influences the quality of identification, the nature of the sample cannot be determined and misidentification occurs as particle size decreases.	Wang & Wang, 2018; Kotar et al., 2022; Zakeri et al., 2020
Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC-MS)	A technique for separating and analyzing volatile or complicated chemical molecules. Thermal breakdown products of microplastics are detected using this approach, and the results are matched to a database to determine polymer type.	Can identify a wide spectrum of microplastics, is appropriate for studying complicated polymer mixtures, requires minimal sample preparation and quantitative analysis is feasible.	The destructive process necessitates careful and extensive preparation and can result in difficult-to-analyze pyrolysis products.	Kedzierski et al, 2019; Chen et al., 2020c; Cho et al., 2023; Picó & Barceló, 2020; Becker et al. 2020

Raman Spectroscopy	A laser is aimed at a sample in Raman Spectroscopy, and the scattered light is collected and	A non-destructive, very easy, and quick approach that identifies the	Can be limited in recognizing certain types of polymers, cannot be	Luo et al., 2022; Lee & Chae, 2021;
	evaluated). It is based on the Raman effect, which is the scattering of light by a material that causes the wavelength of the scattered photons to change.	chemical content and structure of the material.	suited for extremely minute particles, and requires clean surface and reference standards.	Liu et al., 2022b; Sobhani et al., 2019 & 2020; Larkin, 2011
Scanning Electron Microscopy (SEM)	The primary working concept of the Scanning Electron Microscope (SEM) is that it uses released electrons. The scanning electron microscope uses kinetic energy as its working principle to create information from electron interactions with compounds.	Gives high-resolution photographs of the sample surface, enables size and shape analysis, and is suitable for both qualitative and quantitative research.	It is a tructive procedure with information ohemical composition nece that equipment experie specific and	Chen et al., 2020c; Veerasingam et al., 2020a; Luo et al., 2022; Huang et al., 202; Wang & Wang, 2018

Dynamic Light Scattering (DLS)	A laser beam illuminates the sample, and the fluctuations of scattered light are measured by a fast photon detector at a specified scattering angle. DLS sensors measuring at a fixed angle can identify the mean particle size in a narrow size range.	A non-destructive approach that provides information on the particle size distribution can be employed for qualitative and quantitative research.	It cannot be appropriate for particles with low concentrations and little information about their chemical makeup.	Chicea, 2020; Pecora, 2000; Caputo et al., 2021; Luo et al., 2022; Thaiba et al., 2023
X-ray Fluorescence (XRF)	The X-ray fluorescence effect is dependent on atoms in the sample being excited. A primary X-ray, which is commonly generated in an Xray tube, hits an atom's inner shell electron and ejects it from the atom.	Gives information on the sample's elemental composition, is a nondestructive method, and can be used for qualitative and quantitative analysis.	It cannot be suited for low-concentration particles, it can be unable to differentiate between different types of plastics, and it has limited information on chemical structure.	Jozanikohan & Abarghooei, 2022; Yadav et al., 2023; Turner, 2017; Massos & Turner, 2017

Laser Induced Breakdown Spectroscopy (LIBS)	It is a type of atomic emission spectroscopy that learns more about the sample’s composition by generating plasma on its surface. A spectrometer can detect element-specific radiation produced by plasma decay.	Provides information on the elemental composition of the sample, non-destructive technique, and can be used for qualitative and quantitative analysis.	It cannot be appropriate for particles with low concentrations and insufficient chemical structural information.	Sommer et al., 2022; Gondal & Siddiqui, 2007; Chen et al. 2020d; Zeng et al., 2021
FTIR (Fourier Transform	As IR photons travel through a sample, some are absorbed while others flow through (is	Can detect a wide range of microplastics and nondestructive procedures,	When the target particles are smaller than 20 mm, the accuracy suffers. A	Campanale et al., 2023; Chen et alc., 2020;
Infrared Spectroscopy)	transmitted). The spectrum of light absorbed contains qualitative “fingerprints” of the sample’s makeup.	and can be used for and quantitative analysis, and molecular micro-FTIR can examine particles as tiny as 20 mm.	reference library is required to identify unfamiliar particles; The instruments are costly, and expert operators are required.	Vinay Kumar et al., 2021; Lee & Chae, 2021; Fadlelmoula et al., 2022;

3.6. Conclusion

Following a review of articles and books on the use of FTIR to identify and quantify microplastics in environmental samples, FTIR is seen as a powerful technique for analyzing microplastics in environmental samples (Chen et al., 2020b; Campanale et al., 2023; Thomas et al., 2017). The ability of FTIR to detect and quantify microplastics in a variety of sample types, including water, sediment, and biota, is highlighted in the article. The technique has also been discovered to be effective in identifying the types of microplastics found in samples, such as fibers or fragments (Chen et al., 2020c; Luo et al., 2022; Zakeri et al. 2020). To better identify the polymer types of the microplastics being analyzed, FTIR is more reliable than other techniques (Hidalgo-Ruz et al., 2012).

The article also discusses some of the FTIR technique's limitations, such as sample preparation issues, interference from background materials, and challenges in accurately quantifying microplastics at low concentrations (Lee & Chae, 2021; Vogt et al., 2019; Thomas et al., 2017). The outstanding increase in the use of FTIR in microplastic identification and quantification shows the importance and strength of the technique over others. This has been critically analyzed in the review giving the pros and cons of the other techniques in comparison with the FTIR spectroscopy.

In summary, an insight that could be gained from the use of FTIR in microplastic detection is that the technique provides a powerful analytical toolset. FTIR allows for precise identification and quantification of microplastics; offers insights into their chemical composition, size, and shape; facilitates tracking of pollution sources, and contributes to understanding their environmental interactions and fate. This comprehensive approach aids in formulating targeted strategies for mitigating the impact of microplastics on ecosystems.

It is therefore recommended that researchers continue to examine and develop novel FTIR methods to solve the issue of the technique's speed, accuracy, and sensitivity for improved microplastic detection and quantification, especially at low concentrations. Collaborations in R&D activities with analytical chemists and engineers, among others, can assist in achieving this. To conduct a complete examination of samples from various environmental matrices, it is advised that FTIR be used in conjunction with other methods to compensate for its shortcomings.

Having established FTIR as a reliable method for microplastic identification, this research now applies this analytical approach to investigate the microplastic problem in Lake Volta, beginning with an assessment of the primary source: residential solid waste management practices.

CHAPTER FOUR

Assessment of Residential Solid Waste Management Practices Along Lake Volta, Ghana

Abstract

Effective solid waste management (SWM) remains a major environmental and publichealth challenge, particularly for freshwater shore communities. This study provides the first lake-proximal, mixed-methods assessment of household SWM along Lake Volta that verifies self-reports by inspecting waste receptacles across 16 communities. A paper-based, interviewer-administered household survey was combined with key-informant interviews and field observations, and strands were integrated through joint displays. Awareness was high: 90.6% knew the harms of improper SWM, yet only 40.0% knew about segregation and 26.2% about e-waste. Verified composition showed 57.5% of households dominated by organics and 40.0% by plastics; paper, wood and other categories were rare. Disposal practices were suboptimal: dustbin use was 1.6%, compared to dumping near homes, 51.9%. Dambai had a composting facility, but most areas relied on open dumping. Burning at dumping sites remained dominant across the communities. Environmental Health Officers identified inadequate funding, obsolete equipment and limited sanctioning authority as core constraints. Findings deliver decision-ready, locality-specific evidence: decentralised organics treatment where organics dominate; targeted plastic recovery and improved container access around markets; and school-based and public ewaste/segregation education. Strengthening coordination and resource optimization can advance sustainable SWM, thereby realising Sustainable Development Goals 3 and 6 (Good Health and Well-being and Clean Water and Sanitation) around Lake Volta outcomes.

4.1. Introduction

Lake Volta, the world's largest man-made lake by surface area, spans approximately 8,500 square kilometres, cutting across multiple regions in Ghana (Gordon et al., 2013; Ndehedehe et al., 2017). This vast freshwater body plays a pivotal role in Ghana's socioeconomic landscape, supporting fishing, agriculture, tourism, and transportation, while also serving as a critical water source for household use and hydropower generation via the Akosombo Dam (Amevenku et al., 2019; Yeleliere et al., 2018). Lake Volta contributes 16% of Ghana's inland fish capture and 85% of its national freshwater fish production (FAO, 2016), reinforcing its ecological and economic significance. However, poor solid waste management (SWM) increasingly threatens preserving its ecological integrity.

The growing population, urbanization, and economic activities around Lake Volta have led to serious waste management challenges, exacerbated by inadequate infrastructure and ineffective disposal practices (Awafo et al., 2023; Boadi & Kuitunen, 2005; Bour, 2019; Khan et al., 2022; Lissah et al., 2021). Waste accumulation along the shoreline and surrounding communities continues to degrade the environment, mirroring Ghana's broader SWM issues (Miezah, Obiri-Danso, et al., 2015). The absence of proper collection, disposal, and recycling facilities results in waste, particularly plastics, that may be infiltrating the lake through runoff and direct dumping. Plastics break down into microplastics, leading to contaminating of drinking water sources and endangering aquatic life, with potential implications for food safety, public health, and biodiversity (Salikova et al., 2024). The presence of solid waste in the environment is also known to facilitate disease proliferation and diminish the lake's aesthetic and recreational value (Acholonu et al., 2023). Moreover, climate change, with rising temperatures and unpredictable precipitation patterns, intensifies the ecological damage linked to poor SWM (Agodzo et al., 2023).

Globally, SWM is a pressing environmental challenge, particularly in developing nations such as Malaysia and India, where rising per capita waste generation, waste composition complexity, and insufficient waste collection pose major hurdles (Batista et al., 2021; Periathamby et al., 2009; Srivastava et al., 2015). Separate collection systems have been recognised as essential in reducing greenhouse gas emissions and enhancing waste management efficiency (Calabrò, 2009). Additionally, waste-to-energy conversion offers a potential solution for sustainable SWM, particularly in emerging economies like India (Shah et al., 2021; Singh et al., 2011). The zero-waste movement and related waste minimization strategies are also gaining traction worldwide (Khan et al., 2022; Song et al., 2015). Despite ongoing efforts, effective waste management remains a global challenge in the 21st century, necessitating evidence-based interventions and comprehensive policy frameworks (Wilson & Velis, 2015). Governance issues further complicate SWM, as sustainable development goals (SDGs) rely on well-structured policies, enforcement mechanisms, and public participation (Rodić & Wilson, 2017). Meanwhile, research and technological advancements continue to reshape municipal waste management, with evolving strategies to enhance sustainability (Ding et al., 2021; Khan et al., 2022).

In Ghana, research on SWM challenges highlights inefficient collection, limited recycling initiatives, and inadequate disposal facilities (Adu-Boahen et al., 2014; Appeaning Addo et al., 2020; Awafo et al., 2023; Lissah et al., 2021). A lack of public awareness and participation further exacerbates the issue (Lissah et al., 2021). While various studies have assessed waste management systems across different regions, limited research exists on waste generation and disposal practices within communities along Lake Volta. Critical data gaps remain regarding waste types, collection methods, transportation, and disposal techniques in these communities, making it challenging to design effective, locationspecific waste management interventions.

This work addresses the lack of verified, locality-level evidence on household waste composition along Lake Volta. The study examines residents' perceptions of local waste management strategies and incorporates insights from environmental officers to assess existing policies and identify areas for improvement. By addressing these critical gaps, this study contributes to the development of sustainable waste management frameworks tailored to the unique needs of communities surrounding Lake Volta.

4.2. Materials and Methods

4.2.1. Study Area Description

This study was carried out in some selected communities along Lake Volta whose SWM practices could have a dire effect on the waterbody (Figure 4.1). The lake lies in the West African state of Ghana, between longitude 1° 30’W and 0° 20’E and Latitude 6° 15’N and 9° 10’N. It spans over 6 Regions (Eastern, Volta, Oti, Northern, Savannah, and Bono East) and about 26 Districts/Municipalities of rural and urban communities in Ghana.

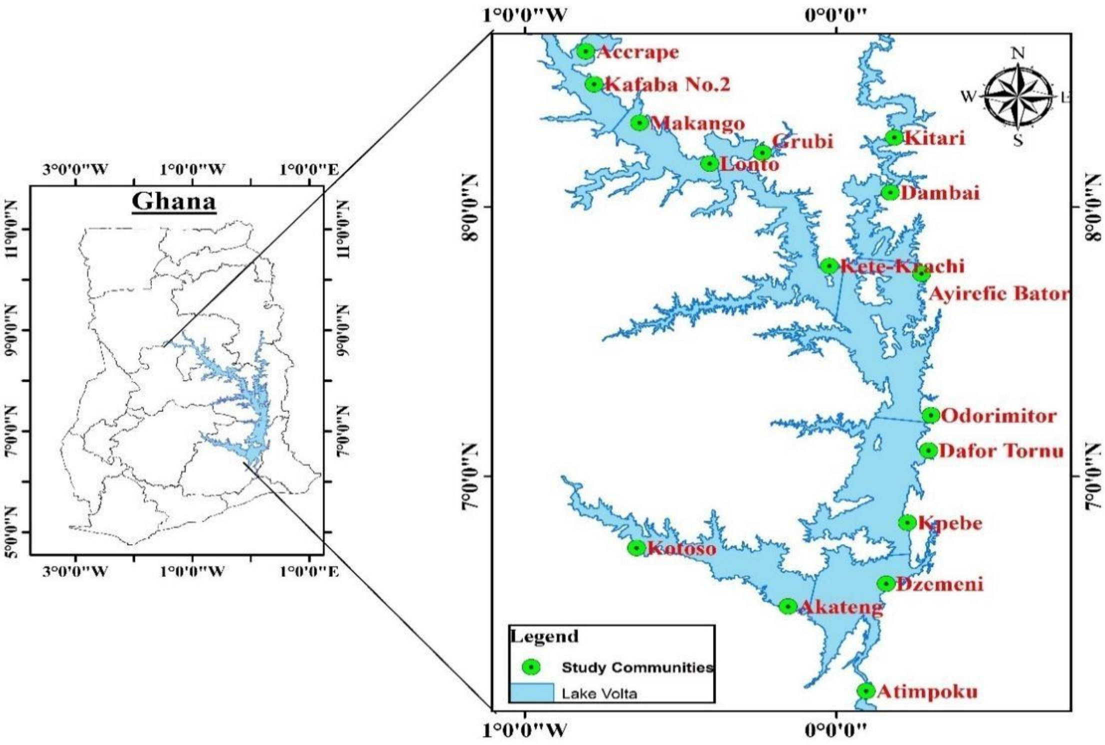


Figure 4.1: A map showing communities along Lake Volta where the study was conducted

As shown in Figure 4.1, two communities each were selected from the eight divisional strata used by the FAO fisheries for data collection purposes (Béné, 2007; Karikari et al., 2013). These two communities serve as the entry and exit of each stratum, indicating the upstream and downstream waste management of each stratum. These strata are stratum I (Akaten & Kotoso), also known as the Afram arm; stratum II (Atimpoku & Dzemeni), the Lower main body; stratum III (Kpebe & Dafor Tornu), the Middle main body; stratum IV (Odormitor & Ayirefie Battor), the Upper main body; stratum V (Dambai & Kitari), the Oti River arm; stratum VI (Kete-Krachi & Grubi), the Lower Volta riverine body; stratum VII (Lonto & Makango), the Middle Volta riverine body; and stratum VIII (Kafaba No. 2 & Accrape), the Upper Volta riverine body. These communities rely wholly on the Lake for transportation, agriculture, economic activities, domestic use, and fishing.

4.2.2. Study Design

The study utilised a mixed research approach to assess SWM in the communities along the Lake, incorporating both qualitative and quantitative data collection techniques. Qualitative methods included in-depth key informant interviews, physical observations, photographs, and video recordings. The study ensured comprehensive engagement with stakeholders vested in effective municipal SMW, minimizing any potential biases. Following the approach of (Appeaning Addo et al., 2020), the study targeted households along the lake since they are very close to the major water body and their SMW practices will have a dire effect on the quality of the water body, traditional authorities, assembly members, market traders, and municipal environmental officers for the needed data. Questionnaires were used to retrieve information from households, while interviews were conducted with key informants such as environmental officers, traditional authorities, assembly members, and market leaders.

4.2.3. Household Sampling

Three major sampling techniques were employed in selecting households for the study: stratified, judgmental/purposive, and simple random. Because the lake is already put into different strata by FAO for fisheries statistics purposes, the study selected two communities from each stratum using the stratified sampling methodology (Karikari et al., 2013). This selection was done to support the work to be done in Chapters five- seven. Judgmental or purposive sampling was employed to select houses located close to the lake, as their waste management practices were deemed to have significant potential impacts on the lake. This approach focused specifically on these households rather than the entire community, making a probabilistic sampling method—which requires consideration of the community's total population—unsuitable for this study. After locating these houses, simple random sampling was used to select the households to be included in the survey. For the household survey, eligible respondents were household heads; when unavailable, another adult household member knowledgeable about their solid-waste practices was interviewed. In rare cases where the most knowledgeable person was <18 years, interviews proceeded only with guardian consent and minor assent. Key informants (e.g., environmental health officers, assembly members, market leaders, traditional authorities) were recruited using purposive sampling. In total, 20 households were randomly interviewed in each community along the shores to ensure balanced results and avoid disproportionate influence from any single community. This is also because geographically, households near the water body are in a prime location where pollutants, including plastics, are most likely to enter the water system, whether through direct disposal or runoff from homes. Since the population of only the households along the lake could not be determined, a non-probabilistic sampling approach, which does not involve the total population of the community, was chosen. The 16 communities selected were Kotoso in the Kwahu East District, Akateng in the Upper Manya Krobo District, Atimpoku in the Asuogyaman Municipality, Dzemeni in the South Dayi Municipality, Kpebe in the North Dayi District, Dafor Tornu in the Kpando District, Odormitor in the Biakoye District, Ayirefie Battor and Dambai in the Krachi East Municipality, Kete-Krachi in the Krachi West Municipality, Grubi in the Krachi Nchumuru District, Kitari and Lonto in the Kpandai District, and finally Makango, Kafaba No.2 and Accrape in the East Gonja District. Therefore, 320 households were interviewed. The sample size was calculated using the Cochran's sample size formula (Ahmed, 2024) (Equation 4.1.):

$$Z^2.p(1-p)$$

$$n_0 = \frac{}{E2} \qquad (4.1)$$

Where:

- n_0 = initial sample size for large population
- Z = z-value (1.96 for the 95% confidence interval used)
- P = estimated population proportion (0.5 for the unknown population of households)
- E = margin of error (0.055 used in this study)

Households were eligible for inclusion if they were located within 500 m of the lakeshore and fell within the selected community, with priority given to those situated inside the 90 m buffer zone. This prioritisation aligns with Ghana's national buffer-zone guidelines, which recommend a 60–90 m setback for lakes (Ministry of Water Resources, Works and Housing, 2011, p. 23). A total of 36 key informants were interviewed to validate and verify information obtained from households, including environmental officers who also shared the challenges they face. The selection of informants was based on the identification of individuals within the specified groups who were both knowledgeable about the subject of interest and willing to participate in the study. Additional participants were reached through a snowball sampling approach, whereby initial informants referred other stakeholders of the community within the catchment area. Environmental officers from the 12 districts (Kwahu East District, Upper Manya District, Asuogyaman District, South Dayi, North Dayi District, Kpando Municipal, Biakoye District, Krachi East Municipal, Kpandai District, Krachi Nchumuru District, Krachi West Municipal, and East Gonja Municipal) covering the 16 communities were also targeted to be included once they agree to participate in the research.

4.2.4. Data Collection

Data for the survey and interviews were collected using closed questionnaires and interview guides. Questionnaires were paper-based and interviewer-administered to accommodate multiple local languages and low literacy. Interviewers read questions aloud, translated where necessary, and recorded responses. Key-informant data were collected via one-on-one, semi-structured interviews using an interview guide; interview duration varied by participant cooperation and availability. Similar to that of Abanyie et al. (2022), the questionnaires mainly focused on areas including the demographic characteristics of the respondent, the household head's socio-economic characteristics, knowledge of community- and household-based SWM practices, awareness and commitment to waste segregation and minimization, and perception of SWM work in the communities by the district assemblies charged with this task. Researchers verified all quantitative data by directly inspecting the household's waste bin during the interview. This included assessing the type of waste storage container used and identifying the predominant waste type to ensure data accuracy. The interview, however, focused more on the waste collection, transportation disposal of waste from the household, and their perception of the management of waste in the area. Due to the distances between sampling communities, data collection took place from the 8th of January to the 20th of May, 2024. The confidentiality of respondents was strictly maintained throughout the study. To ensure this, all personally identifiable information was removed from the dataset, and each respondent was assigned a unique, anonymised code. Data were stored on password-protected computers accessible only to the researcher, and any physical records were kept in locked cabinets. These measures ensured that no individual respondent could be identified from the collected data, in line with ethical research standards.

4.2.5. Data Analysis and Processing

The survey data were cleaned, checked for missing values, and analysed with statistics suited to each outcome (means/medians, crosstabulations and Chi-square), similar to earlier work (Taye et al., 2024). Interview data were examined using Framework Analysis: transcripts were coded to predefined domains (e.g., awareness/minimization; storage; disposal; collection/transport; satisfaction; institutional capacity; barriers/facilitators), summarised into a matrix that compared cases across communities, and interpreted for patterns, with reliability checks and an audit trail to ensure rigour. The Pearson correlation was used to ascertain the relationship of key quantitative data. The results of the study were presented in the form of pie charts, tables, bar charts, and crosstabulations with chi-square tests using a 95% level of confidence (Abanyie et al., 2022; Odonkor & Sallar, 2021). All questionnaires from the field were analysed using SPSS version 27 and GraphPad/ Prism version 10.0. However, the interviews were coded for presentation.

The formula for calculating the average age (Equation 4.2):

$$\text{Weighted Average Age} = \frac{\sum(Number\ of\ Respondents\ in\ Age\ Group \times Representative\ Age\ of\ Group)}{Total\ Number\ of\ Respondents} \qquad \textbf{(4.2)}$$

Where **Σ** denotes the sum of all age groups; **The number of respondents in the Age Group** is the count of respondents within each specific age range; **The Representative Age of Group** is an estimated midpoint or representative age for each age range (e.g. 8.5 was chosen for the below 18 years age range; The total number of Respondents is the sum of all respondents across all age groups.

4.2.6. Ethical Consideration

Since human subjects were involved in the study and are part of this research, ethical clearance was first sought from the Ethics Review Committee of the University of Energy and Natural Resources (UENR) and a copy of that is attached as plate 3 in the supplementary. However, before this study was carried out on the field, permission was also obtained from the Municipal Assembly, traditional leaders, the Assembly members, Unit Committee members of the localities, other stakeholders, and the household heads of the sampled households.

4.3. Results

4.3.1. Demographic Characteristics

A total of 320 questionnaires were administered, yielding a 100% response rate. The survey covered demographic characteristics, including the age and gender of respondents (Table 4.1). The survey revealed that 255, representing almost 80% of the respondents from the communities of interest, were between the ages of 25 and 63 (Table 4.1). The majority of respondents (33.8%) were aged between 25 and 35. Based on equation (4.2), the calculated average age of the respondents was approximately 37.5 years. There was a slight male predominance of 170 (53.1%) with 150 (46.9%) females. This distribution highlights a slightly higher male participation in the survey.

Educational qualifications of the HHs also varied, with 143 (44.7%) of the HHs having no formal education, 134 (41.9%) possessing basic education, 38 (11.9) with secondary (high school) education, and only 5 (1.6%) with tertiary education. The data indicate a low level of formal education among household heads, which may impact their awareness and practices regarding waste management. Also, the majority of the HHs (40.3%) were engaged in fishing, followed by trading (27.5%), farming (16.3%), private company employees (5.9%), others, including the unemployed, apprentices, students, mechanics, and others (5.0%), and government employees (3.8%).

Table 4.1: Demographic characteristics of households living along the Lake Volta

Demographic Data	**Number**	**Percentage (%)**
Respondent's Age		
Below 18	8	2.5
18 – 24	41	12.8
25 – 34	108	33.8
35 – 44	81	25.3
45 – 63	66	20.6
Above 63	16	5.0
Respondent's Gender		
Male	170	53.1
Female	150	46.9
HH's Educational Qualifications		
No formal education	143	44.7
Basic Education	134	41.9
Secondary Education	38	11.9
Tertiary Education	5	1.6
HH's Profession		
Government Employee	12	3.8
Private Employee	19	5.9
Trading	88	27.5
Retired	4	1.3
Fisherman	129	40.3
Farmer	52	16.3
Others	16	5.0

4.3.2. Household's Waste Management Awareness

Table 4.2 shows that awareness of the effects of improper waste management is notably high across localities, with 90.6% of respondents recognizing its impact. This demonstrates a foundational understanding of environmental degradation and public health problems linked with poor waste management techniques. However, understanding waste segregation is low, with only 40% of participants familiar with the concept and 60% unaware. This knowledge gap shows that source separation techniques may not have been fully integrated into local waste management systems, which is crucial for effective recycling and resource recovery. Similar to previous studies by Yin et al. (2021), 47.8% of respondents recognise the value of waste segregation, whereas the remaining 52.2% do not. Similarly, only 26.2% of respondents are aware of electronic waste (e-waste). As a result, most e-waste is likely to be improperly disposed of, leading to pollution, health risks, and economic losses. Toxic chemicals from discarded electronics can contaminate soil, water, and air, increasing the risk of respiratory diseases, neurological disorders, and food chain contamination.

Although 60.5% of respondents are aware of the principle of waste minimization, a much higher 95% express commitment to minimizing waste; this suggests that some participants claimed to support waste minimization because it is seen as the "right" thing to do, even if they lack full awareness of the concept. Localities such as Akateng, Dzemeni, Lonto, Makango, and Kafaba No. 2 exhibit high levels of awareness and commitment across most metrics. Moreover, respondents in communities like Grubi, Kafaba No. 2, and Kitari reveal lower awareness levels in areas such as waste segregation and electronic waste management, despite general recognition of improper waste effects. Chi-square tests indicate significant differences in waste management awareness and practices among localities (df =15, p < 0.05). These findings highlight the variability of knowledge and behaviour, emphasizing the necessity for targeted interventions that address distinct community needs.

Table 4.2: Awareness Level of Respondents in Households along Lake Volta

Name of Locality	Aware of the Effect Aware of Waste Importance of Aware of Aware of the Committed to of Improper Waste Segregation Segregation Electronic Waste Principle of Waste								Waste Minimization		Minimization	
	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
Kitari	18	2	8	12	12	8	3	17	15	5	20	0 (0%)
Kete-Krachi	16 (80%)	4 (20%)	(30%)	(70%)	(47.4 %)	(52.6 %)	8 (40%)	12 (60%)	(60%)	(40%)	(80%)	4 (20%)
Grubi	19 (95%)	1 (5%)	6 (30%)	14 (70%)	13 (68.4 %)	6 (31.6 %)	6 (30%)	14 (70%)	8 (40%)	12(60 %)	20 (100%)	0 (0%)
			(40%)	(60%)	(60%)	(40%)			(75%)	(25%)	(100%)	
			6	14	9	10			12	8	16	
(90%) (10%)		(15%) (85%)										
Ayirefie Battor	16 (80%)	4 (20%)	(40%)	(60%)	(60%)	(40%)	3 (17.6%)	14 (82.4%)	(80%)	(20%)	20 (100%)	0 (0%)
Dambai	14 (73.7%)	5 (26.3%)	15 (75%)	5 (25%)	15 (75%)	5 (25%)	11 (55%)	9 (45%)	9 (45%)	11 (55%)	20 (100%)	0 (0%)
Akateng	20 (100%)	0 (0%)	12 (60%)	8 (40%)	15 (75%)	5 (25%)	9 (45%)	11 (55%)	7 (35%)	13 (65%)	20 (100%)	0 (0%)
Kotoso	14 (70%)	6 (30%)	12 (60%)	8 (40%)	14 (70%)	6 (30%)	4 (20%)	16 (80%)	15 (75%)	5 (25%)	20 (100%)	0 (0%)
Atimpoku	14 (70%)	6 (30%)	2 (10%)	18 (90%)	3 (15%)	17 (85%)	4 (20%)	16 (80%)	11 (55%)	9 (45%)	17 (85%)	3 (15%)
Dzemeni	20 (100%)	0 (0%)	11 (55%)	9 (45%)	11 (55%)	9 (45%)	5 (25%)	5 (75%)	13 (65%)	7 (35%)	19 (95%)	1 (5%)
Kpebe	20 (100%)	0 (0%)	10 (50%)	10 (50%)	10(50 %)	10 (50%)	6 (30%)	14 (70%)	12 (60%)	8 (40%)	13 (65%)	7 (35%)
Dafor Tornu	20 (100%)	0 (0%)	5 (25%)	15 (75%)	8 (40%)	12 (60%)	1 (5%)	19 (95%)	16 (80%)	4 (20%)	20 (100%)	0 (0%)
Odormitor	20 (100%)	0 (0%)	9 (45%)	11 (55%)	10 (50%)	10 (50%)	8 (40%)	12 (60%)	16 (80%)	4 (20%)	19 (95%)	1 (5%)
Total Percentage	288 (90.6%)	30 (9.4%)	8 (40%)	12 (60%)	12 (47.8 %)	8 (52.2 %)	83 (26.2%)	234 (73.8%)	16 (60.5 %)	4 (39.5 %)	(95%)	16 (5%)
Chi-Square value (df, p-value)	48.644 (15, <0.001)		49.197 (15, <0.001)		58.128 (15, <0.001)		32.583 (15, 0.005)		28.985 (15, 0.016)		63.158 (15, <.0.001)	

Lonto	20 (100%)	0 (0%)	10 (50%)	10 (50%)	10 (50%)	10 (50%)	3 (15%)	17 (85%)	13 (68.4 %)	6 (31.6 %)	20 (100%)	0 (0%)
Makango	20 (100%)	0 (0%)	4 (20%)	16 (80%)	4 (20%)	16 (80%)	6 (30%)	14 (70%)	11 (55%)	9 (45%)	20 (100%)	0 (0%)
Kafaba No. 2	20 (100%)	0 (0%)	0 (0%)	20 (100 %)	0 (0%)	20 (100 %)	0 (0%)	20 (100%)	11 (55%)	9 (45%)	20 (100%)	0 (0%)
Accrape	18 (90%)	2 (10%)	10 (50%)	10 (50%)	6 (30%)	14 (70%)	6 (30%)	14 (70%)	8 (40%)	12 (60%)	20 (100%)	0 (0%)
			128	192	152	166			193	126	304	

4.3.3. Solid Waste Generation and Management

Respondents stated the dominant daily waste produced in their households, and the interviewer confirmed this through inspection of the household dustbin or any container used for storage. The results are presented in Table 4.3. All percentages refer to households in which the stated waste type was confirmed as dominant. Overall, 57.5% of households had organic waste as dominant, and 40.0% had plastic; wood (0.6%), paper (0.9%), and other (0.9%) were rare. By locality, organic waste dominated in Dafor Tornu (80%), Kotoso (60%), and Kpebe (60%), while plastic dominated in Atimpoku (75%) and was also common in Dzemeni (55%) and Grubi (55%). A Pearson chi-square test showed significant differences in dominant waste types across localities (p = 0.002), indicating variation in household waste composition between communities.

Table 4.3: Distribution of the number of households and their predominant daily waste production

Name of the Locality	**Organic Waste**	**Plastic Waste**	**Paper Waste**	**Wood**	**Others**
Akateng	13 (65%)	7 (35%)	0 (0%)	0 (0%)	0 (0%)
Kotoso	12 (60%)	8 (40%)	0 (0%)	0 (0%)	0 (0%)
Atimpoku	5 (25%)	15 (75%)	0 (0%)	0 (0%)	0 (0%)
Dzemeni	9 (45%)	11 (55%)	0 (0%)	0 (0%)	0 (0%)
Kpebe	12 (60%)	8 (40%)	0 (0%)	0 (0%)	0 (0%)
Dafor Tornu	16 (80%)	4 (20%)	0 (0%)	0 (0%)	0 (0%)
Odormitor	15 (75%)	5 (25%)	0 (0%)	0 (0%)	0 (0%)

Ayirefie Battor	9 (45%)	7 (35%)	1 (5%)	0 (0%)	3 (15%)
Dambai	13 (65%)	7 (35%)	0 (0%)	0 (0%)	0 (0%)
Kitari	13 (65%)	7 (35%)	0 (0%)	0 (0%)	0 (0%)
Kete-Krachi	10 (50%)	8 (40%)	1 (5%)	1 (5%)	0 (0%)
Grubi	8 (40%)	11 (55%)	0 (0%)	1 (5%)	0 (0%)
Lonto	13 (65%)	7 (35%)	0 (0%)	0 (0%)	0 (0%)
Makango	12 (60%)	7 (35%)	1 (5%)	0 (0%)	0 (0%)
Kafaba No. 2	14 (70%)	6 (30%)	0 (0%)	0 (0%)	0 (0%)
Accrape	10 (65%)	10 (50%)	0 (0%)	0 (0%)	0 (0%)
Total percentages	184 (57.5%)	128 (40.0%)	3 (0.9%)	2 (0.6%)	3 (0.9%)
Chi-Square value (df, pvalue)	95.685 (60, 0.002)				

Figure 4.2 shows how waste from homes is stored in different locations before disposal. The most common primary storage method before disposal is the use of polyethylene/plastic bags (47.5%). Metallic or rubber buckets are the second most popular storage technique (24.1%), while only a small percentage (1.6%) use a trash management company's dustbin. Also, 26.9% of respondents store their waste in different types of containers, such as baskets and old saucepans, among others. Polyethylene/plastic bags are the primary storage method in Akateng (85%), Kafaba No. 2 (65%), and Accrape (70%). Areas such as Atimpoku (60%) and Ayirefie Battor (55%) rely more on buckets. The chisquare test (p-value of 0.000) demonstrates statistically significant variances in waste storage systems across different localities, indicating a wide range of behaviours. These

findings emphasise the significance of understanding local practices to enhance waste management infrastructure and access to appropriate disposal facilities

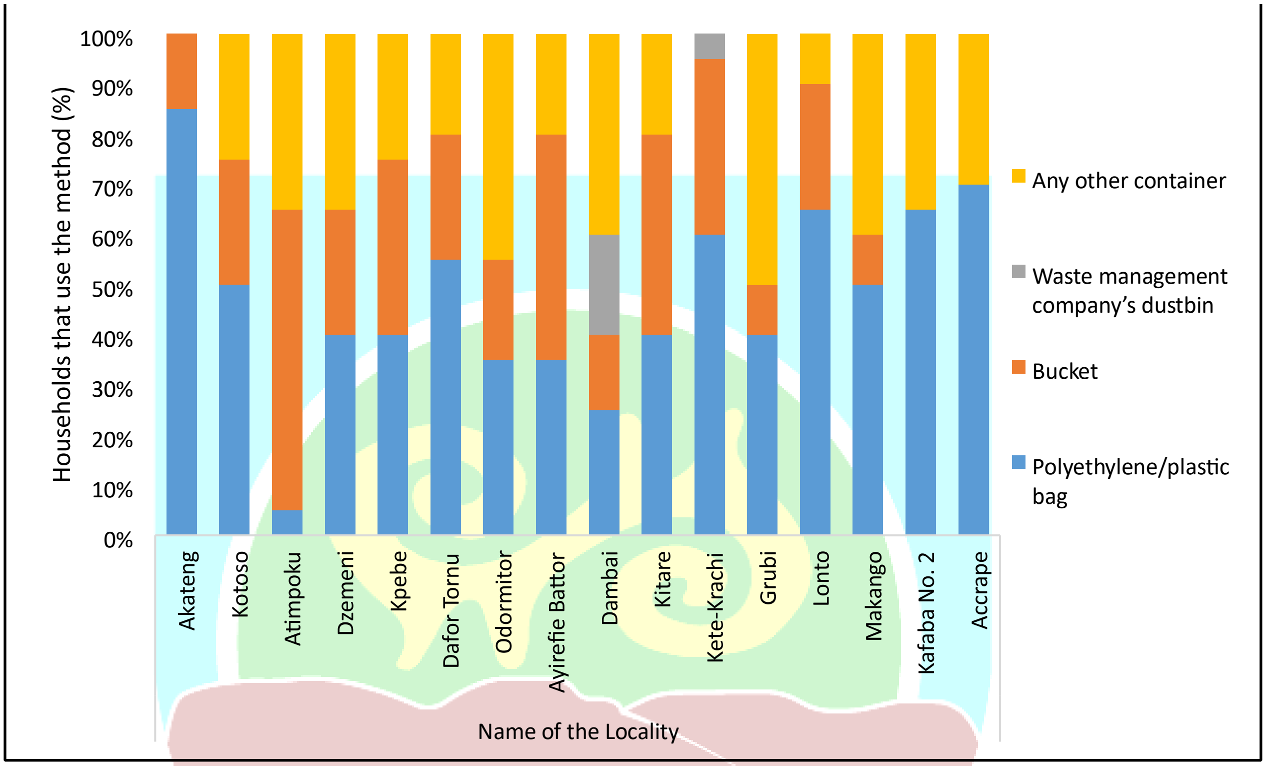


Figure 4.2: Solid Waste storage practices of households along Lake Volta before disposal

Despite the high awareness level of the negative impacts of improper waste management among respondents, their actual waste disposal practices largely contribute to pollution. A significant number, 166 (51.9%) of the households (Table 4.4) dispose of waste in spaces (be it open spaces and dugouts) near their homes, indicating a reliance on informal waste disposal methods, which can lead to environmental degradation and health risks. Additionally, 79 (24.7%) use designated refuse dump sites. Only 15.6% of homes use skip containers, mostly in places where these services are more easily accessible, such as Atimpoku (85%), Dzemeni (75%), and Kete-Krachi 70%. About 5.3% of homes report roadside dumping, with Odormitor (30%) and Kpebe (20%) having the highest rates. Only a small number of localities, like Dambai (25%) and Kete-Krachi (15%), use door-to-door solid waste collection, which is the least popular disposal technique (2.5%). Plate 4.1 illustrates the main places of disposal observed during field visits: (a) Atimpoku and (b) Dzemeni show communal skip containers—often rusty or not collected on schedule—while (c) Dambai with a well-managed skip container, and (d) Kotoso depicts an informal dumping in open spaces near dwellings. These field observations are consistent with the survey results, where 51.9% of households disposed of waste near the house, 24.7% used designated dump sites, and only 15.6% used skip containers, with marked differences across communities ($\chi^2 = 372.905$; df = 60; $p < 0.001$).

Table 4.4: Waste disposable methods in households of communities along Lake Volta

Name of the Locality	The place where households dispose of their waste				
	In the skip container	By roadside	In a space near the house	Door-todoor waste collections	Designated refuse dump site
Akateng	0 (0%)	0 (0%)	15 (75%)	0 (0%)	5 (25%)
Kotoso	0 (0%)	3 (15%)	9 (45%)	0 (0%)	8 (40%)
Atimpoku	17 (85%)	1 (5%)	2 (10%)	0 (0%)	0 (0%)
Dzemeni	15 (75%)	0 (0%)	0 (0%)	0 (0%)	5 (25%)
Kpebe	0 (0%)	4 (20%)	11 (55%)	0 (0%)	5 (25%)
Dafor Tornu	0 (0%)	0 (0%)	6 (30%)	0 (0%)	14 (70%)
Odormitor	0 (0%)	6 (30%)	14 (70%)	0 (0%)	0 (0%)
Ayirefie Battor	0 (0%)	1 (5%)	15 (75%)	0 (0%)	4 (20%)
Dambai	4 (20%)	0 (0%)	9 (45%)	5 (25%)	2 (10%)
Kitari	0 (0%)	3 (15%)	9 (45%)	0 (0%)	8 (40%)
Kete-Krachi	14 (70%)	0 (0%)	0 (0%)	3 (15%)	3 (15%)

Grubi	0 (0%)	0 (0%)	14 (70%)	0 (0%)	6 (30%)
Lonto	0 (0%)	0 (0%)	16 (80%)	0 (0%)	4 (20%)
Makango	0 (0%)	0 (0%)	10 (50%)	0 (0%)	10 (50%)
Kafaba No. 2	0 (0%)	0 (0%)	15 (75%)	0 (0%)	5 (25%)
Accrape	0 (0%)	2 (10%)	16 (80%)	0 (0%)	2 (10%)
Total percentages	50 (15.6%)	17 (5.3%)	166 (51.9%)	8 (2.5%)	79 (24.7%)
Chi-Square Value (df, p-value)	372.905 (60, 0.000)				

(a)

(b)

(c) (d)

Plate 4.1: Different types of disposal methods (a) Atimpoku (b) Dzemeni (c) Dambai and (d) Kotoso (Photographs taken during the field assessment)

4.3.4. Solid Waste Collection and Transportation

SWM includes the collection and transportation of waste from the source of generation to transfer stations and, eventually, disposal sites. This is a crucial aspect of waste management since if waste is generated, it must be collected and transported. The investigation revealed two major solid waste collection methods: door-to-door and Communal Container Collections (truck systems). Door-to-door or house-to-house collections are generally done by small businesses using tricycles and take place in mostly urban communities where there are either skip containers or not. However, the truck system is managed by district assemblies, or the service is contracted out to waste management service providers. These truck systems, too, operate mostly in urban areas where there are skip containers. Out of the 16 settlements visited, only Dambai, Kete-Krachi, Atimpoku, Akateng, and Dzemeni had this vehicle system for waste collection and transportation. Due to the rusty nature of the skip container situated about 400 m from the town, the community prefers to use other options; hence, the truck rarely visits them.

In-depth interviews were conducted to assess the community's waste collection and transportation challenges. This was to understand the frequency of visits by waste management and sanitation officers to transport waste. Out of all the interviewees or informants, over 60.0 % reported never seeing waste management visiting their localities for waste collection purposes. One interviewee stated:

"The community has not conducted a cleanup exercise in a long time. Additionally, no officer from the assembly has ever come for waste collection, possibly due to the absence of a skip container in the area." Another interviewee said:

"Because our place is far, the assembly does not visit us. The community leaders do not care about waste management since it is common practice for everyone to clean their homes and dispose of refuse at the designated site. It is only during elections that Assemblymen encourage citizens to undertake cleanup exercises."

4.3.5. Waste Disposal Practices

Aside from Dambai which has a 400-ton state-of-the-art integrated recycling and compost plant designed for recycling and compost but is currently into composting only, most of the municipalities dump the collected waste finally at an open dump site that does not meet a landfill status. These dumping sites observed in the communities, as shown in Plate 4.2, were mostly open as indicated by Vinti et al. (2023).

(a) **(b)**

Plate 4.2: Open Dumping Site located at (a) Kotoso and (b) Kete-Krachi

When asked about common waste management practices at community dumpsites due to the assembly's absence, 94% of the informants said household waste is typically burned. This finding aligns with Abanyie et al. (2022), where 93% of households managed their waste through burning.

One informant commented:

"We usually burn our household waste in our pits or at our dumping sites. Sometimes, you may see some young people collecting plastic to sell. Scrap dealers also visit to pick up some of the waste or buy it."

However, waste burning, according to (Vinti et al., 2023), is a common practice in Ghana, especially in rural communities, and this practice has very high health risks for the spread of contaminants such as carbon monoxides (CO), carbon dioxide (CO_2), dioxins and furans, poly aromatic hydrocarbons (PAHs), heavy metals, etc. in the air contributing to global warming, as was suggested by Owusu-Ansah et al. (2022).

4.3.6. Stakeholder Satisfaction with the Municipal Waste Removal System

Table 4.4 shows respondents' satisfaction with the current SWM system in various communities. A considerable proportion of respondents expressed displeasure with the system, with 39.1% indicating dissatisfaction and 20.6% reporting extreme discontent. This suggests that the majority of residents are dissatisfied with waste collection services in their localities. On the other side, only 2.5% of respondents were very satisfied, while 14.4% were satisfied, indicating a general lack of pleasure. The highest proportion of dissatisfaction was recorded at Kotoso (45%), Odormitor (55%), and Ayirefie Battor (65%). In contrast, areas like Akateng (35%) and Kitari (35%) had slightly higher levels of satisfaction, with fewer people reporting unhappiness. The chi-square test (p-value = 0.000) demonstrates statistically significant differences in satisfaction levels between the locales, implying that how waste management services are perceived varies significantly among communities. These findings emphasise the importance of improving SWM systems to address widespread unhappiness and ensure more effective waste management.

Table 4.5: Respondent's satisfaction level with the present municipal waste removal system

Name of the Locality	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
Akateng	0 (0%)	7 (35%)	5 (25%)	8 (40%)	0 (0%)
Kotoso	0 (70%)	0 (0%)	3 (15%)	8 (40%)	9 (45%)
Atimpoku	2 (10%)	1 (5%)	1 (5%)	10 (50%)	6 (30%)
Dzemeni	2 (10%)	4 (20%)	2 (10%)	6 (30%)	6 (30%)
Kpebe	0 (0%)	6 (30%)	5 (25%)	7 (35%)	12 (10%)
Dafor Tornu	0 (0%)	0 (0%)	12 (60%)	7 (35%)	1 (5%)
Odormitor	0 (0%)	0 (0%)	0 (0%)	9 (45%)	11 (55%)
Ayirefie Battor	0 (0%)	0 (0%)	3 (15%)	13 (65%)	4 (20%)
Dambai	2 (10%)	1 (5%)	7 (35%)	8 (40%)	2 (10%)
Kitari	0 (0%)	7 (35%)	10 (50%)	3 (15%)	0 (0%)
Kete-Krachi	2 (10%)	4 (20%)	5 (25%)	7 (35%)	2 (10%)
Grubi	0 (0%)	0 (0%)	5 (25%)	8 (40%)	7 (35%)
Lonto	0 (0%)	6 (30%)	5 (25%)	8 (40%)	1 (5%)
Makango	0 (0%)	4 (20%)	5 (25%)	4 (20%)	7 (35%)
Kafaba No. 2	0 (0%)	2 (10%)	3 (15%)	11 (55%)	4 (20%)
Accrape	0 (0%)	4 (20%)	4 (20%)	8 (40%)	4 (20%)
Total Percentages	8 (2.5%)	46 (14.4%)	75 (23.4%)	125 (39.1%)	66 (20.6%)
Chi-Square Value (p-	141.501 (0.000)	value)			

4.3.7. Insights from Municipal/District Environmental Health Officers

Consultations with Environmental Health Officers responsible for managing solid waste in the districts and municipalities revealed several challenges. The officers acknowledged significant gaps in service coverage, with some areas not receiving waste management services. They attributed these shortcomings to a lack of authority to make financial and administrative decisions, coupled with inadequate financial resources. Additionally, they reported that outdated vehicles and equipment frequently break down, and lack spare parts for vehicles. Lack of technical capacity also sometimes affect operations and to foster compliance. An important issue that was raised was the lack of cooperation and poor response to waste minimization (reuse/recycling) on the part of the populace in communities where they render their services.

4.4. Discussion

4.4.1. Demographics and Waste Management Practices

The demographic profile of respondents indicates that most were in early and middle adulthood (25 to 63), which is crucial as these age groups are typically responsible for managing household waste. This demographic trend aligns with Ghana’s 2021 Census report, which shows a shift towards a younger population (Ghana Statistical Service, 2021b). The study also revealed a low percentage (2.5%) of respondents below 18 years. Although females generally outnumber males in Ghana, the study found a slightly higher male participation population (Ghana Statistical Service, 2021a). This could be because men are mostly the household heads in Ghanaian homes. The census also showed a higher male population in rural areas, consistent with this study's findings, as 75% of the surveyed communities were rural.

Additionally, the study highlights a high rate of school dropouts, particularly among males who abandon education for immediate financial ventures like fishing. It confirms earlier research by Ananga (2013), which stated that local labour market opportunities appeared to prompt children to pursue income-generating activities instead of going to school. Additionally, the findings corroborated with earlier studies by Amevenku et al. (2019) and Obongo et al. (2021) on the dropout trend. That is, about 14 HH (44.7) had no formal education, with only 5 (1.6%) having attained a tertiary education. This is evidenced by the fact that fishing was the major occupation (40.3%) of household heads, followed by trading (27.5%) and farming (16.3%). This demographic distribution suggests that most of the lakeside houses, even in urban areas like Dambai, Kete Krachi, Dzemeni, and Atimpoku, are predominantly occupied by fisherfolk, reflecting their educational backgrounds.

4.4.2. Household Waste Management Awareness

An impressive 90.6% of respondents were aware of the adverse effects of poor waste management practices, similar to earlier work (Fadhullah et al., 2022). Nevertheless, just 40% of participants knew what waste segregation was, which was far below the 67.4% recorded by Owusu-Ansah et al. (2022). The disparities in the results show that there is a substantial knowledge gap among the residents along the Lake Volta, which may impede recycling and resource recovery initiatives. The same was true for electronic waste (ewaste) and its hazardous substances, including heavy metals and persistent organic pollutants (POPs), of which just 26.2% of respondents knew about. This corroborates initial studies by Twumasi (2017) that indicated there is a lack of knowledge on electronic waste and a disconnect between awareness and practice. Because if respondents were truly aware of e-waste and its hazardous nature, they might have separated it from the other types of waste just as it is being practised in other jurisdictions. Conversely, 95% of respondents said they were committed to adopting waste minimization practices even though 60.5% of respondents were aware of the waste minimization principle. This is indicative of the fact that although the people do not know the principles in theory, they have vowed to adopt them since they trust it to be the right thing to do. Previous research by Odonkor & Sallar (2021) found that 81.1% of respondents were interested in waste minimization, which is consistent with this high willingness.

4.4.3. Improving Solid Waste Management (SWM)

4.3.3.1. Solid Waste Generation and Management

The survey shows that organic waste forms the dominant household stream overall (57.5%), with plastics second (40.0%), but the composition differs markedly by locality (χ^2, p = 0.002). These differences are plausibly explained by variation in settlement type, livelihoods, and consumption patterns. Rural lakeside communities such as Dafor Tornu (80%), Kotoso (60%), and Kpebe (60%) rely heavily on fresh foods and primary production (e.g., farming/fishing), which generates peels, leftovers, and other biodegradable residues—thus a higher share of organics. In contrast, localities with greater commercial activity and market throughput—Atimpoku (75% plastics), Dzemeni (55%), and Grubi (55%)—tend to accumulate packaging-related plastics (bottles, sachets, wraps) from retail trade and transit, raising the plastic fraction.

Socioeconomic mix and purchasing behaviour influence the outcome. Peri-urban/market areas usually have higher consumption of packaged foods and beverages than agrarian settlements, and this shifts the composition toward plastics. Proximity to market days can temporarily increase packaging waste, while larger household size and intensive cooking raise the organic fraction in rural settings. Since many of the communities—Kotoso, Akateng, Kpebe, Dafor Tornu, Odormitor, Kitari, Grubi, Kafaba No. 2, Lonto, and Accrape—are rural, a high percentage of households reported organic waste as the predominant waste.

The general dominance of organics with a substantial plastic component aligns with reports from comparable settings (Suryati et al., 2021; Asase et al., 2009). Divergence from the study by Yin et al. (2021) that found plastics as the leading stream, it is consistent with different sampling frames and demographics, notably, more urbanised populations like Atimpoku and Dzemeni with higher packaged-goods penetration. These locality-specific drivers indicate that management responses should be differentiated: organics-heavy communities benefit from source separation and decentralised composting/biogas, whereas plastics-heavy localities require targeted plastic recovery (buy-back points, producer takeback) and more frequent collection around markets and transit corridors.

There is also a noticeable dissatisfaction with waste management systems among respondents, similar to the findings (Sheburah Essien & Spocter, 2024). In-depth interviews revealed that waste management inefficiencies, such as delays in collecting skip containers, further contribute to dissatisfaction. These findings align with (Denteh et al., 2018), who reported similar issues. The need for better waste management infrastructure and consistent services is evident to reduce improper disposal practices and improve overall waste management satisfaction.

The study reveals significant variations in waste storage methods across communities. Only 1.6% of respondents used dustbins from waste management companies, suggesting limited access to formal waste collection services or a lack of trust in their effectiveness. Also, likely due to the availability, affordability, and convenience, most households preferred to store their waste in polyethene/plastic bags. However, this practice raises environmental concerns, as plastic waste is non-biodegradable and can contribute to pollution if not properly managed. The chi-square test ($p = 0.000$) confirms that waste storage methods differ significantly across localities. This research highlights the necessity of understanding community-specific waste management behaviours when developing successful solid waste disposal and collection systems. Addressing these gaps necessitates targeted initiatives such as providing low-cost dustbins, upgrading trash collection systems, and encouraging sustainable storage habits.

Despite widespread awareness of the detrimental effects of poor waste management, actual disposal methods were problematic. More than half of households (51.9%) disposed of solid waste in areas near their dwellings, using informal techniques that endanger the environment and health. This aligns with previous studies (Miezah, Obiri-Danso, et al., 2015; Owusu-Ansah et al., 2022), which highlights the persistent reliance on unsafe waste disposal techniques in many communities. Furthermore, 24.7% used designated solid waste sites, whereas only 15.6% used skip bins, most notably in Atimpoku (85%) and Dzemeni (75%). This shows that access to suitable waste disposal facilities is associated with disposal behaviours. However, door-to-door or house-to-house solid waste collection services were uncommon, with only 2.5% of homes, primarily in Dambai and Kete-Krachi, utilizing this service. Chi-square analysis ($p < 0.001$) reveals substantial differences in community waste management strategies. These findings highlight the critical need for enhanced waste management infrastructure and formalised disposal procedures to reduce reliance on risky informal practices. To solve these difficulties, (Appeaning Addo et al., 2020) propose investing in waste collection systems, increasing access to skip bins, and educating communities on sustainable waste disposal methods.

4.3.3.2. Waste Disposal System

Aside from Dambai, which has a cutting-edge recycling and composting plant which can process 400 metric tonnes of solid waste per day, though it is currently solely being utilised for composting, other towns employ open dumping sites that do not fulfil landfill criteria (Plate 4.2) prescribed by Ozbay et al. (2021). The practice of using open dumping sites, as revealed in the current study, contributes to the dispersion of waste of all forms, especially plastic waste, which takes a longer time to decompose into micro and nanoplastics, posing environmental and health risks to nearby communities. This observation was also made by a respondent in Appeaning Addo et al. (2020).

Burning was the most popular solid waste disposal method, according to 94% of informants. This behaviour is consistent with the findings of Abanyie et al. (2022), which found that 93% of families burnt their waste. However, burning solid waste has substantial health and environmental dangers since it emits dangerous chemicals such as carbon monoxide, dioxins, and heavy metals (Iqbal et al., 2020). The burning of waste could contribute to global warming (Owusu-Ansah et al., 2022). Building on the findings of (Cook et al., 2024), this study also observed that some informal recovery sector individuals, engaged in sporadic recycling activities, such as collecting plastic waste for resale.

4.4.4. Stakeholder Roles in Enhancing SWM

Stakeholders, including municipal/district assemblies and community members, play a crucial role in enhancing SWM in communities along Lake Volta. Satisfaction with the current SWM system varies greatly by community, just as (Wang et al., 2022) reported. A sizable proportion of respondents reported unhappiness (39.1%) or serious dissatisfaction (20.6%). Only 14.4% were satisfied, and only 2.5% reported being satisfied. The highest levels of dissatisfaction were observed in Kotoso (45%), Odormitor (55%), and Ayirefie Battor (65%). In contrast, Akateng and Kitari had slightly higher levels of satisfaction. The chi-square test (p-value = 0.000) revealed significant disparities in satisfaction levels among localities, demonstrating that perceptions of SWM services fluctuate greatly.

Consistent with the findings of (Kwakye et al., 2024), consultations with municipal and district environmental health officers revealed challenges such as inadequate funding, outdated equipment, and limited administrative decision-making authority. Additionally, officers noted that households were not cooperating well with the adoption of waste minimization techniques contrary to their claims. To strengthen SWM systems and alleviate widespread discontent, these findings highlight the necessity of more public participation, capacity building, and resource allocation.

By combining survey estimates with key-informant insights and on-site verification, this study provides decision-ready evidence for differentiated interventions, decentralised organics treatment in organics-heavy communities and targeted plastic recovery around market centres.

4.5. Conclusion

Households along Lake Volta confront substantial obstacles in waste management practices, including low levels of education, sporadic waste collection, and the utilization of deleterious disposal methods such as burning and uncontrolled dumping. Although 90.6% of respondents recognise the environmental and health ramifications of improper waste management, and 95% express a willingness to adopt sustainable practices, knowledge gaps in waste segregation and e-waste handling impede progress. With waste composition varying across localities, 57.5% of households primarily generate organic waste, while 40% predominantly produce plastic waste, highlighting the need for tailored waste management interventions. Widespread dissatisfaction with waste management services may stem from inadequate infrastructure, financial constraints on the part of the waste managers, and insufficient public engagement. Addressing these challenges requires collaborative efforts among stakeholders, including relevant ministries, to ensure appropriate resource allocation to Environmental Officers at municipal and district levels, enhance infrastructure, and expand public education initiatives on waste segregation and e-waste management. Replicating successful innovations, such as Dambai's composting facility, and incorporating waste management education into academic curricula are crucial steps toward sustainable solutions. Government allocation of research funding for continuous research and monitoring is vital to refine strategies, address emerging challenges, and advance Ghana's progress toward achieving Sustainable Development Goals 3 and 6.

The study's sampling strategy and statistical tools exhibited limitations, despite its significant contributions to the field. Future investigations employing probabilistic sampling techniques and involving the entire population instead of only the residents along the lake may yield more robust data to corroborate and strengthen the study's conclusions. An error margin of less or equal to 5% could equally be used to ensure precision.

4.6. Bridging to Chapter 5: From Land-Based Practices to Aquatic Contamination

The findings from this chapter reveal that inadequate solid waste management in lakeshore communities—characterised by high plastic waste generation, prevalent dumping and burning practices, and limited formal collection—creates direct pathways for macroplastic debris to enter Lake Volta. Once in the aquatic environment, these plastics undergo photodegradation and mechanical fragmentation, generating secondary microplastics. Given this clear linkage between land-based waste handling and potential aquatic pollution, the logical next step is to investigate whether these management failures have translated into measurable microplastic contamination in the lake. Therefore, Chapter 5 shifts focus from the sources on land to the state in the water, employing spatial modeling to quantify and map the distribution of microplastics in Lake Volta's surface water and sediments.

CHAPTER FIVE

Charting Pollution: Spatial Modeling of Microplastics Distribution in Sediments and Surface Water from Lake Volta

Abstract

Microplastic (MP) pollution poses a significant threat to aquatic environments, leading to extensive research into its occurrence, distribution, and ecological effect. This study looked at MP levels, spatial variability, and their composition in surface water and sediment from Lake Volta. It provided information on pollution hotspots and ecological risks. Samples were collected from 16 lakeside communities and processed using a combination of pretreatment, density separation, oxidation, and identification using Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR). Results revealed an average MP Concentration of 15.88 ± 10.69 MPs/L in surface water and 148.33 ± 119.35 MPs/kg in sediment. Concentrations ranged from 2 to 54 MPs/L and 20 to 460 MPs/kg in water and sediment respectively. The majority of MPs were fibres and polyethylene, with black particles dominating water samples and blue ones more common in sediment. Size analysis showed most MPs in water were between 1001–5000 µm, while sediment MPs predominantly measured 501–1000 µm. A statistically significant difference in MP abundance between water and sediment was observed ($\chi^2 = 20.83889$, df = 1, $p < 0.0001$), a finding that was confirmed using Dunn's Test (mean rank difference = -15.125, $z = -4.56$, and $p < 0.001$). Spatial distribution mapping identified hotspots in strata SII (2U), SVI (6D), and SVII (7D). The Polymer Hazard Index (PHI) values of 14.76 (water) and 13.02 (sediment) suggest notable polymer contamination. However, the Ecological Risk Index (ERI) values of 30.52 and 27.44 indicate a relatively low ecological risk. Considering Lake Volta's role in sustaining fisheries and livelihoods, immediate interventions, such as enhanced plastic waste management, community education, and adoption of nature-based solutions, are critical to mitigating the growing threat of MP pollution.

5.1. Introduction

Microplastics (MPs) are plastic particles that measure 5 mm or smaller. They have become a global environmental issue and are found in marine waters, freshwater systems, wastewater, food, air, and even drinking water, both bottled and tap (Andoh et al., 2024; WHO, 2019). Their increasing presence in the environment has attracted significant attention and is now seen as a priority alongside climate change. The United Nations Sustainable Development Goal (SDG) 14, Target 1, specifically addresses marine debris, highlighting its growing threat. MPs present serious risks to ecosystems, especially aquatic ones. Their potential effects on human health, which remain poorly understood, add urgency to efforts to address this issue (Bexeitova et al., 2024).

Ecosystems are polluted by these particles through wastewater discharge, inadequate waste management, and accidental spills. They come from either primary, which are intentionally made for use in personal care products and plastic pellets, or secondary sources, which are formed when larger plastic items degrade (Akdogan et al., 2023; Vermaire et al., 2017). Despite producing over 380 million tons of plastic each year from 1950 to 2015, only 9% of this was recycled globally, worsening the buildup of plastic waste in the environment (Sharma et al., 2023).

Developing countries are particularly vulnerable to MP pollution due to poor waste infrastructure, weak regulations, and low public awareness (Awewomom et al., 2024; Kibria et al., 2023). Economic challenges and cross-border plastic pollution from wealthier countries worsen the issue (Wang et al., 2022). Ghana, along with many developing nations, faces rising plastic use and ineffective waste disposal, making plastic pollution a growing environmental challenge (Andoh et al., 2024).

Initially, research on MPs concentrated on marine environments, documenting their wide presence, ecological impacts, and bioaccumulation in aquatic organisms (Acharya et al., 2022; Yu & Singh, 2023; Mahu et al., 2024). More recent studies have shifted attention to freshwater systems—lakes, rivers, and streams—which are critical yet often overlooked areas (Egessa et al., 2020; Kumar et al., 2024; Xu et al., 2021). This change reflects a growing understanding of the vulnerability of freshwater bodies and the need for coordinated monitoring and management across both marine and freshwater ecosystems.

In Ghana, research on MPs is still developing, but early studies have found them in key freshwater bodies, raising concerns for aquatic health and food safety. Initial investigations include Adu-Boahen et al. (2020) on River Akora, Blankson et al. (2022) on River Densu, and Boateng et al. (2024) on the lower section of Lake Volta. These studies link the contamination to plastic use, urban runoff, and insufficient waste management. Acquah et al. (2021) highlighted the urgent need for public awareness and targeted research.

Boateng et al. (2024) found MPs in sediments and fish from lower Lake Volta, connecting fishing activities, urban runoff, and nearby communities as sources. However, thorough assessments of other areas of the lake are still lacking. Given Lake Volta's significance as a major freshwater source and an economic lifeline for local communities, this study examines the abundance, distribution, and characteristics of MPs in the sediment and surface water of upper Lake Volta. It also identifies pollution hotspots and assesses the associated ecological risks.

5.2. Materials and Methods

5.2.1. Study Area

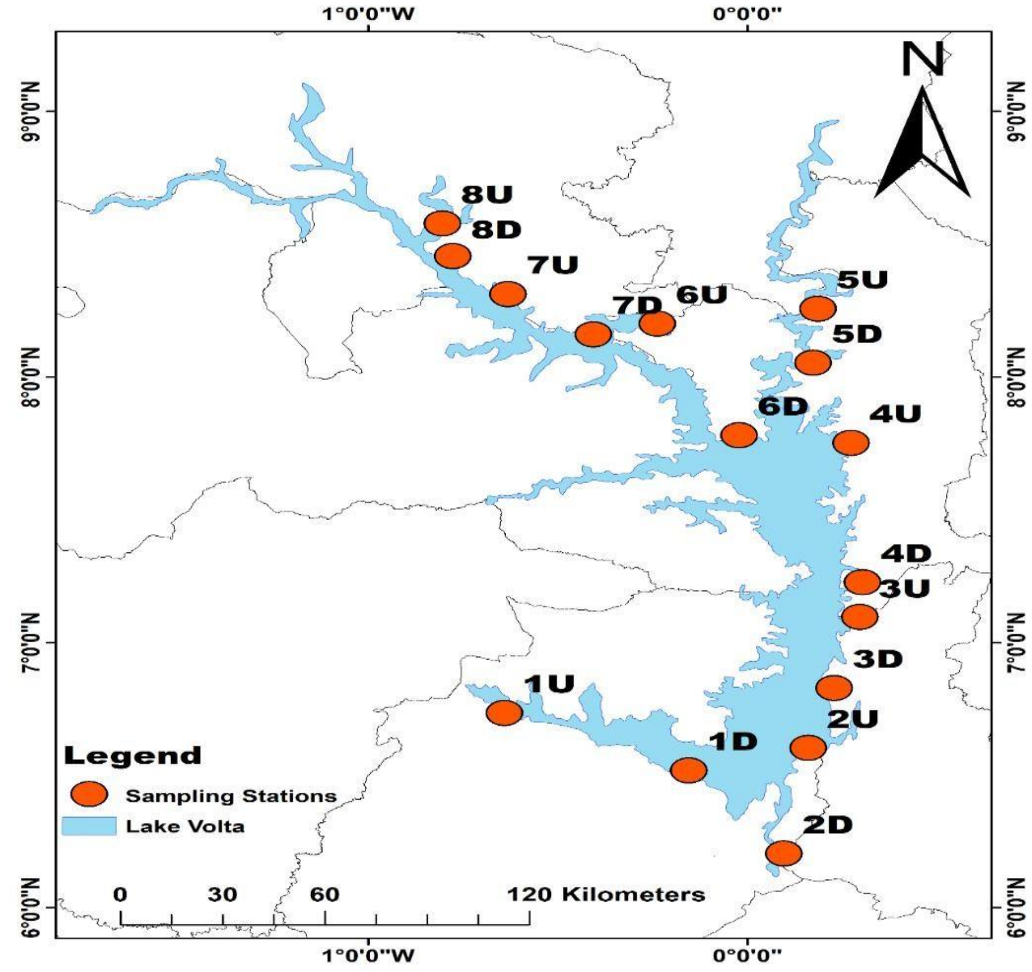


Figure 2.1: Sampling stations along Lake Volta (NB: Stratum Nos. lablled 1 -8 with D-Downstream and U-Upstream)

Lake Volta comprises the Afram Arm (Stratum I – 1D & 1U), the Main Lake (Strata II, III, IV – 2D – 4U), the Oti River (Stratum V- 5D & 5U), and the Volta Riverine (Strata VI, VII, VIII – 6D – 8U) was considered for the study. The lake lies between longitude 1° 30'W and 0° 20'E and Latitude 6° 15'N and 9° 10'N, extending over 250 miles (400 km) and spanning 3283 square miles (8502 km^2), covering over 3.6 percent of Ghana's total surface area (Boateng et al., 2024). Lake Volta serves several purposes beyond generating hydroelectric power. It supports transportation, agriculture, domestic use, fishing, and local economic activities. Market days in the main towns along the lake are important social and economic events. They draw large crowds from nearby communities especially the islands. However, these gatherings have become major sources of environmental pollution. This is mainly due to their informal nature, the widespread use of single-use plastic bags and packaging, and poor waste management systems. Waste collection usually happens two to three days after market days, allowing plastics to build up along the shore and should it rain, they get washed straight into the lake. The calm nature of the lake prevents these plastics from washing back ashore. This situation adds to the problem of microplastics (MPs) in the water. Additionally, the lake is home to aquaculture works and these contribute to plastic pollution.

5.2.2. Sample Collection

Sixteen fishing communities were chosen as sampling stations for the study, with two communities (upstream (U) and downstream (D)) selected from each of the eight Food and Agriculture Organization (FAO) fisheries data collection strata, as shown in Figure 5.1 and Table 5.1. Assisted by artisanal fishermen, a handheld Garmin GPSMAP 67i Global Positioning System (GPS) with an accuracy of ±3.65 meters, manufactured in Taiwan, was used to record coordinates at each sampling station for spatial modelling (Ghansah et al., 2022). Sampling took place in January 2024, at a rising level of the water. This month marked a dry season in Ghana, resulting in minimal rainfall and reduced surface runoff. This was important because it could have influenced the number of MPs in the other selected communities since the study area was large and couldn't be covered in just one day. Conducting the sampling in January allowed for a clear and accurate view of the MPs presence in the lake. Following the bottle sampling technique described by Vermaire et al. (2017) and Masaru et al. (2015), 500 mL glass bottles, decontaminated with deionised water, with metallic lids were used to collect 48 (in triplicate) surface water samples from a depth of 10 to 15 cm in the water column at each station. The samples were properly labelled, transported on ice from the field to the laboratory, and stored at 4°C until analysis. Additionally, 200 g of benthic sediment samples were collected from the same locations in triplicate (n=48) using a Denmark-made van Veen Grab sampler (2500 cm²). Each sediment sample was transferred into labelled, decontaminated glass bottles, thoroughly mixed, and transported on ice at 4°C to the laboratory for MP analysis. All samples were transported to the laboratory on ice within a maximum journey time of four hours, following storage in an ice chest for up to three hours. After each day's sampling exercise, the samples were securely stored while awaiting laboratory analysis.

Table 5.1: Characteristics of the Sample Stations

Station ID	Station Name	Stratum No.	Sampling location	
			Latitude	*Longitude*
1D	Akateng	SI	6.517452	-0.154619
1U	Kotoso		6.734431	-0.640703
2D	Atimpoku	SII	6.203402	0.096132
2U	Dzemeni		6.601997	0.160316
3D	Kpebe	SIII	6.828539	0.228677
3U	Dafor Tornu		7.096558	0.296463
4D	Odormitor	SIV	7.227164	0.303883
4U	Ayirefie Bator		7.752975	0.273589
5D	Dambai	SV	8.054329	0.173664
5U	Kitari		8.257985	0.186018
6D	Kete-Krachi	SVI	7.781517	-0.021963
6U	Grubi		8.201656	-0.237008

7D	Lonto	SVII	8.161278	-0.406054
7U	Makango		8.312814	-0.631061
8D	Kafaba No. 2	SVIII	8.456121	-0.776831
8U	Accrape		8.578424	-0.803729

5.2.3. Sample Analysis

5.2.3.1. Water Samples

The laboratory analysis of water samples was conducted at the Fisheries Laboratory, Department of Marine and Fisheries, University of Ghana, between February and June 2024. The water samples were processed following the laboratory procedures established by the National Oceanic and Atmospheric Administration (NOAA) as described by Masaru et al. (2015). The water samples were sieved with a 5 mm mesh metallic sieve to remove larger particles and impurities (particles above 5mm in diameter). 500 mL of the filtrate was measured using a 1000 mL glass beaker and a Fenton's reagent (20 mL of 30% H_2O_2 and 20 mL of 0.05M ferrous sulphate catalyst) was added. The mixture was left at room temperature (around 30 °C) for five minutes to dissolve all organic matter present before being filtered using glass fiber paper (1.2 µm Whatman GF/C, 47 mm diameter) under a vacuum just like Parvin et al. (2022). The filter paper with the residues was placed in a glass petri dish, covered with aluminum foil, and left to dry in the oven at 60 °C for 24 hours before visual, microscopic, and ATIR-FTIR analyses.

5.2.3.2. Sediment Samples

The sediment samples were homogenised by thoroughly mixing them with a ceramic pestle and mortar following the protocol of Blankson et al. (2022)to ensure no clumps and ovendried for 24 hours at 90 °C in aluminum foil until all moisture was removed. An aliquot (50 g) was passed through stainless steel sieve (5 mm mesh size) and the fraction recovered was oxidised using Fenton's reagent (20 mL of 30% H_2O_2 and 20 mL of 0.05M ferrous sulphate), with the samples heated to 75 °C for 45 minutes for organic matter digestion just as recommended by NOAA and captured by Prata et al. (2019). The oxidised samples were transferred to metal trays, sealed in paper bags, and dried at 50 °C for 24 hours. The dried samples were placed in 10 mL centrifuge tubes with NaCl solution (density $\rho = 1.2$ g/ml) similar to that of Blankson et al. (2022) but with the omission of the use of olive oil, for the density separation. After stirring at 300 rpm for 1 hour, the supernatant was vacuum filtered using glass fiber paper (1.2 µm Whatman GF/C, 47 mm diameter). The residues on the filter paper were placed in a glass petri dish, dried at 60 °C for 24 hours, and preserved for visual, microscopic, and ATR-FTIR analyses.

5.2.4. Visual and Optical Identification

The extracted filtrates were visually inspected one sample after the other, and the needle test was used to locate MPs (Barrows et al., 2018; Malla-Pradhan et al., 2022). The suspected MPs were examined under a Leica EZ4 HD stereomicroscope (Germany) after visual inspection. The number of MPs detected on each filter paper was determined and counted just as was done by Parvin et al. (2022). The MPs were classified based on type (fragments, fibers, pellets, films, or others such as foam, beads, etc.), colour (blue, clear, black, and others such as red, yellow, green, etc.), and size categories (≤50 µm, 51–100 µm, 101–500 µm, 501–1000 µm, and 1001–5000 µm) (Boateng et al., 2024).

5.2.5. ATR-FTIR Analysis

Just like the replicates were examined one by one for each sampling station using the microscopic method described above, the Fourier Transform Infrared (FT-IR) analysis was also carried out individually. The polymer types of the MPs were identified using the Compact FTIR spectrometer ALPHA II (Bruker Nano GmbH, Berlin, Germany) at the Materials Science Engineering Laboratory, University of Ghana. Measurements were conducted in transmittance mode across a wavenumber range of 400–4000 cm^{-1} (Jabeen et al., 2017; Parvin et al., 2022). The spectral data obtained from the ATR-FT-IR analysis were visualised and analysed using the Origin Pro 2025 software. To identify the absorption bands of each polymer, the results were compared with each polymer type reported in the existing literature (Cowger et al., 2020; Parvin et al., 2022).

5.2.6. Quality Assurance and Quality Control

Taking a guide from the previous study by Belontz & Corcoran (2021) quality control was taken seriously in this study. Glasswares with metallic lids were used throughout the sample transportation process so that extra MPs would not be introduced. Only cotton lab coats and nitrile gloves were used to prevent contamination during the laboratory analysis. All glassware utilised in the study was decontaminated with 10% nitric acid for 24 hours, rinsed thoroughly with distilled water, and immediately covered with aluminum foil to avoid air-borne MPs contamination. The laboratory windows remained closed throughout the experiment. When necessary, filtrates in glass Petri dishes from surface water and sediment samples were covered with aluminum foil (Malla-Pradhan et al., 2022; Patra & Baitharu, 2024; Weir et al., 2024). Before the ATR- FT-IR analysis, multiple blank tests were conducted to establish a baseline background before placing samples on the holder for analysis.

5.2.7. Data Analysis

Data analysis was conducted using the GraphPad Prism software version 10.0 and OriginPro 2025 software. The graphical presentations of the MPs from the sediment and water were done using GraphPad Prism 10.0. At every point of analysis, a Shapiro-Wilk test of normality was conducted using the OriginPro 2025 software to ensure the usage of parametric or non-parametric statistics to assess potential relationships between explanatory variables and MPs concentrations. To assess whether differences exist between sites, the sixteen study sites were first divided into two sections – downstream and upstream based on their location in the stratum. All results were considered statistically significant if $p < 0.05$ and run at $\alpha = 5\%$.

5.2.8. GIS Analysis

The ArcGIS software version 10.8 was used during data input, analysis, and mapping similar to that of Talbot et al. (2022). The Lake Volta shapefile was downloaded freely from the online portal of the World Bank Group (World Bank, 2017). The database of MP abundance was created using Arc Catalog. The analysis and mapping were achieved using ArcMap 10.8 extensions. The experimental results from the laboratory analysis of water as well as sediment taken from the sixteen sites along the lake were joined as an Excel file, then, they were converted into shapefiles. Samples were then plotted according to their geographical locations with fixed pie chart sizes to be able to give a better picture of the characteristic being analysed. Additionally, all the overlapping pie charts were rectified using Adobe Illustrator version 2024. Classifications were based on the spatial distribution of the MP pollutant per the data range of each parameter.

5.2.9. Ecological Risk Analysis

The pollution risk of MPs in Lake Volta was evaluated using the Pollution Loading Index (PLI), Polymer Hazard Index (PHI), and Ecological Risk Index (ERI) methods described by Islam et al. (2023). These indices, defined by equations (5.1) – (5.6), are based on the abundance and polymer composition of MPs. The calculations are as follows:

$$PLI_i = \frac{C^i}{C_0} \tag{5.1}$$

$$PLI_{Lake} = \sqrt[n]{PLI_1 \times PLI_2 \times PLI_3 \times \ldots \times PLI_n} \tag{5.2}$$

where C_i is the measured MP abundance at site i, C_0 is the minimum baseline concentration, defined as the lowest MP abundance observed in the lake, and n is the number of stations sampled.

$$PHI_i = \sum_{j=1}^{m} \{\frac{P_{ji}}{C_i} \times S_j\} \tag{5.3}$$

$$PHI_{Lake} = \sqrt[n]{PHI_1 \times PHI_2 \times PHI_3 \times \ldots \times PHI_n} \tag{5.4}$$

Where j is the type of polymer; m is the number of identified polymers; $P_{ji}$is the number of polymers of type j at site i; and $S_j$is the polymer hazard score (provided in Table 5.2)

The Ecological Risk Index (ERI) combines PLI and PHI to evaluate the overall risk level of MP pollution.

$$ERI_i = PHI_i \times PHL_i \tag{5.5}$$

$$ERI_{Lake} = \sqrt[n]{ERI_1 \times ERI_2 \times ERI_3 \times \ldots \times ERI_n} \tag{5.6}$$

Table 5.2: Hazardous MPs and their Hazard Scores (Lithner et al., 2011)

MP Polymer	Monomer	Hazard Scores
Polyethene (PE)	Ethelyn	11
Polystyrene (PS)	Styrene	30
Polyamide (PA)	Amide	47
Polypropylene (PP)	Propylene	1
Polyester (PES)	Ester	4
Polyethylene Terephthalate (PET)	Ethanediol	4

5.3. Results

5.3.1. Microplastics Abundance and Distribution

Following the NOAA guidelines for MP analysis by Masaru et al. (2015), the laboratory analysis confirmed the ubiquitous presence of MPs in at all sampling stations. The surface water collected contained 762 MPs/L (n = 48), while sediment samples recorded 7120 MPs/kg (n = 48). The average abundance was 15.875 ± 10.69 MPs/L (mean ± standard deviation, n = 48) in surface water and 148.333 ± 119.35 MPs/kg (n = 48) in sediment. MP abundance of samples collected in triplicates from the 16 stations ranged from 2 to 54 MPs/L in surface water and 20 to 460 MPs/kg in dry sediment samples. Following the failure to meet normality assumptions as indicated by the Shapiro-Wilk test for both water (W = 0.86, df= 16, p = 0.017) and sediment samples (W = 0.87, df=16, p = 0.031), nonparametric analyses were conducted. The Kruskal–Walli's test found no significant differences in MP concentrations among the sixteen sampling sites or communities for both water (χ^2= 15.00, df = 15, p = 0.451) or sediment (χ^2= 15.00, df = 15, p = 0.451). Likewise, comparison across the eight (8) strata showed no significant variation in MP concentrations for water (χ^2= 9.79, df = 7, p = 0.201) and sediment (χ^2= 2.89, df = 7, p = 0.895). However, a significant difference in MP abundance was observed between the two matrices, with sediment samples showing significantly higher concentrations than water (χ^2= 20.84, df =1, $p < 0.0001$). The post-hoc analysis using Dunn's test with Bonferroni correction confirmed that sediment samples had significantly higher MPs concentrations than water samples (mean rank difference = -15.125, z = -4.56, and $p < 0.001$).

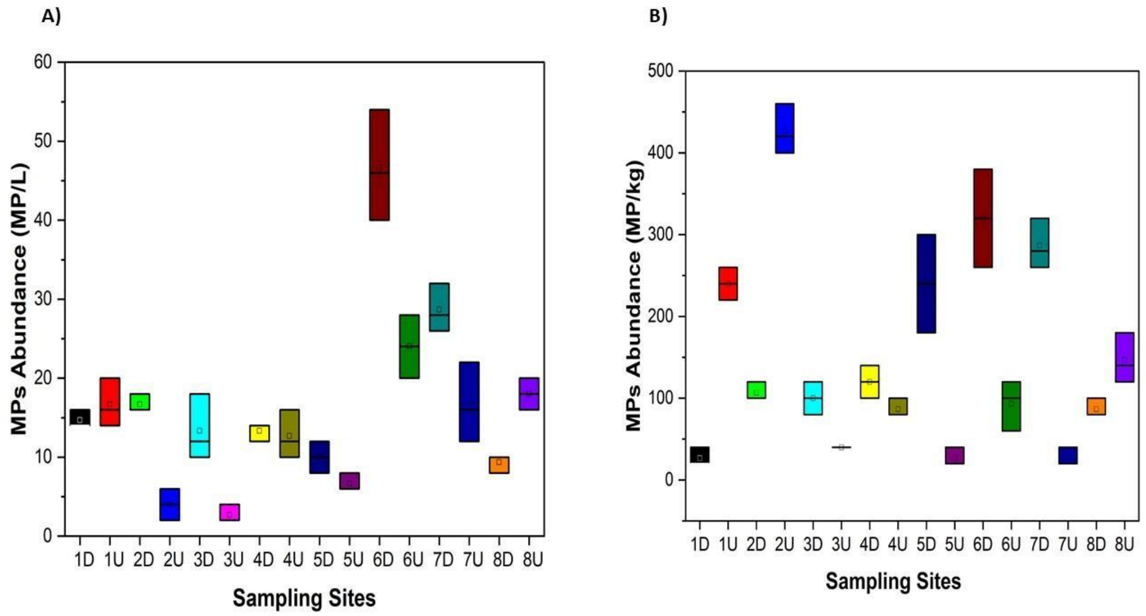


Figure 5.2: Distribution of MPs found in A) Surface Water Samples and B) Sediment Samples from Lake Volta

As illustrated in Panels A and B of Figure 5.2, the abundance of MPs varied between surface water and sediment samples across different stations. Notably, station 6D exhibited the highest MP concentration in surface water, while station 2U showed the greatest accumulation in sediment. This variation in MP distribution might result from the complex transport and deposition mechanisms influenced by local hydrodynamics, sedimentation rates, and anthropogenic activities. The presence of wider whiskers at stations such as 2U and 5D suggests greater variability in sediment deposition, potentially indicating localised hotspots of MP accumulation.

A comparative analysis of the two panels reveals that certain stations, including 6D and 7D, consistently exhibit elevated MP concentrations in surface water and sediment, suggesting persistent pollution hotspots. Conversely, stations such as 3U and 5U demonstrated minimal MP abundance across both matrices, implying limited MP retention in these areas. Additionally, the significantly higher MP abundance in the sediment at station 5D, compared to relatively low levels in surface water, suggests a dominant deposition process rather than active transport at this location. These findings emphasise the role of environmental factors in shaping MP distribution patterns in aquatic systems.

5. 3.2. Spatial Models of the Characteristics of MPs

5. 3.2.1. Characterisation of MPs across Sampling Stations

To assess the characteristics of MPs collected from various sampling stations, the particles were categorised based on shape (fragment, fibre, pellet, film, and others, including foams and sheets), color (blue, clear, black, and others such as yellow, green etc.), and size classes (<50 µm, 51–100 µm, 101–500 µm, 501–1000 µm, and 1001–5000 µm).

Fibres were identified as the predominant MP type across both surface water and sediment matrices. As illustrated in Panels A and B of Figure 5.3, fibres were present at all sampling stations, with stations 4D and 8D exclusively containing fibres in all matrices analysed.

Additionally, in water sediment samples, fibres were the sole MP type detected at stations 2D and 5U. Overall, sediment samples showed a significantly higher proportion of fibres (75.28%) compared to other MP categories, while fibres dominated surface water samples even more prominently, accounting for 90.81% of total MPs. Although fragments and films were also detected in notable quantities, their relative abundance was substantially lower.

The spatial variability in MP color distribution across sampling stations is depicted in Panels C and D. Black MPs were the most frequently identified color in surface water samples, constituting 41.21% of the total MPs. In contrast, blue MPs were the most dominant in water sediment samples, representing 34.68% of the total MPs. Clear and other colours like yellow, green, etc. were also detected in lower quantities. Notably, blue was the only colour of MPs detected in the sediment sample from 3U.

Size distribution trends, as shown in Panels E and F, further illustrate variations between environmental matrices. In surface water samples, the majority of MPs (31.76%) were larger than 1000 µm, whereas water sediment samples predominantly contained MPs within the 501–1000 µm range (27.68%). MPs smaller than 50 µm were the least abundant in both matrices, accounting for 8.92% in surface water and 4.49% in sediment samples. These findings highlight the variability in MP characteristics and emphasise the role of environmental matrices in shaping their distribution patterns.

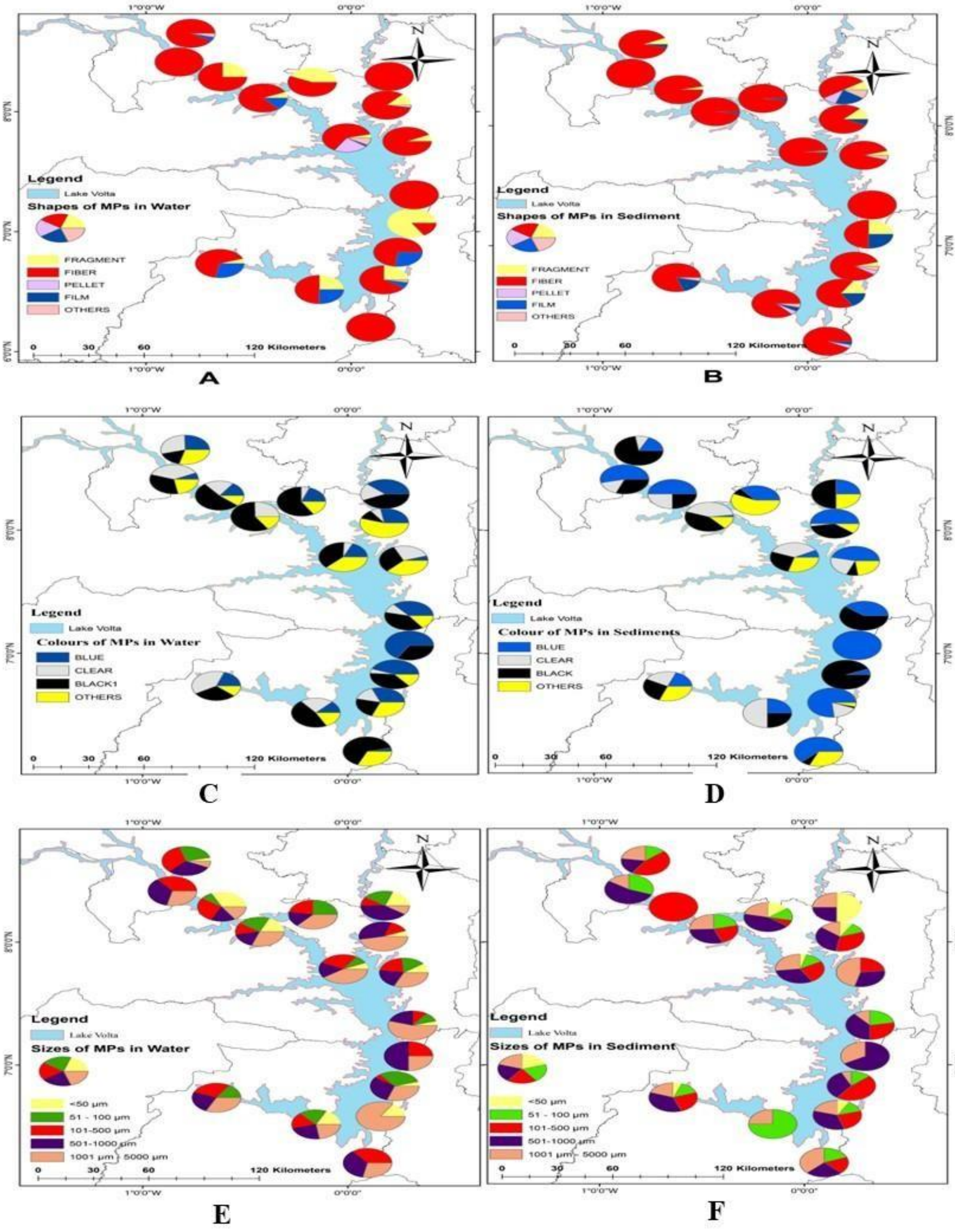


Figure 5.3: Spatial Models of the Morphological Distributions of MPs (Shapes, Colours, and Sizes) from Surface Water (A, C, and E and Sediment (B, D, and F) respectively

5.3.2.2. Polymer Composition

The Fourier-transform infrared (FTIR) spectra of the major synthetic polymers identified in this study are characterised by key absorption bands. Polyethylene (PE) exhibits strong C–H stretching vibrations of CH_2 groups (2915–2848 cm^{-1}), with weaker bands for CH_2 bending (1470–1460 cm^{-1}) and rocking (730–720 cm^{-1}). Polyester and the specific polyester polyethylene terephthalate (PET) share a strong C=O stretch (~1715 cm^{-1}) and C–O stretching (1240–1100 cm^{-1}); PET is further indicated by aromatic C=C stretching (1400–1600 cm^{-1}). Polystyrene (PS) displays aromatic C–H stretching (~3025 cm^{-1}), aromatic ring C=C stretches (~1600, 1490 cm^{-1}), and bands characteristic of a monosubstituted benzene ring (700–750 cm^{-1}). Polyamide (Nylon) shows strong N–H stretching (3300–3400 cm^{-1}) and amide C=O stretching (1640–1650 cm^{-1}). Polypropylene (PP) is characterised by C–H stretches (2950–2850 cm^{-1}) and CH_3 bending vibrations (1450–1375 cm^{-1}). The FTIR spectra for the identified polymers are shown in Figure 5.4.

Based on this analysis, polyethylene was the most predominant synthetic polymer, constituting 31.76% of microparticles in surface water and 34.27% in sediment (Figure 5.5). Other primary polymers identified were polystyrene, polypropylene, polyester, and polyethylene terephthalate. FTIR confirmation was achieved for approximately 81% of visually identified microparticles in surface water samples and 88% in sediment samples.

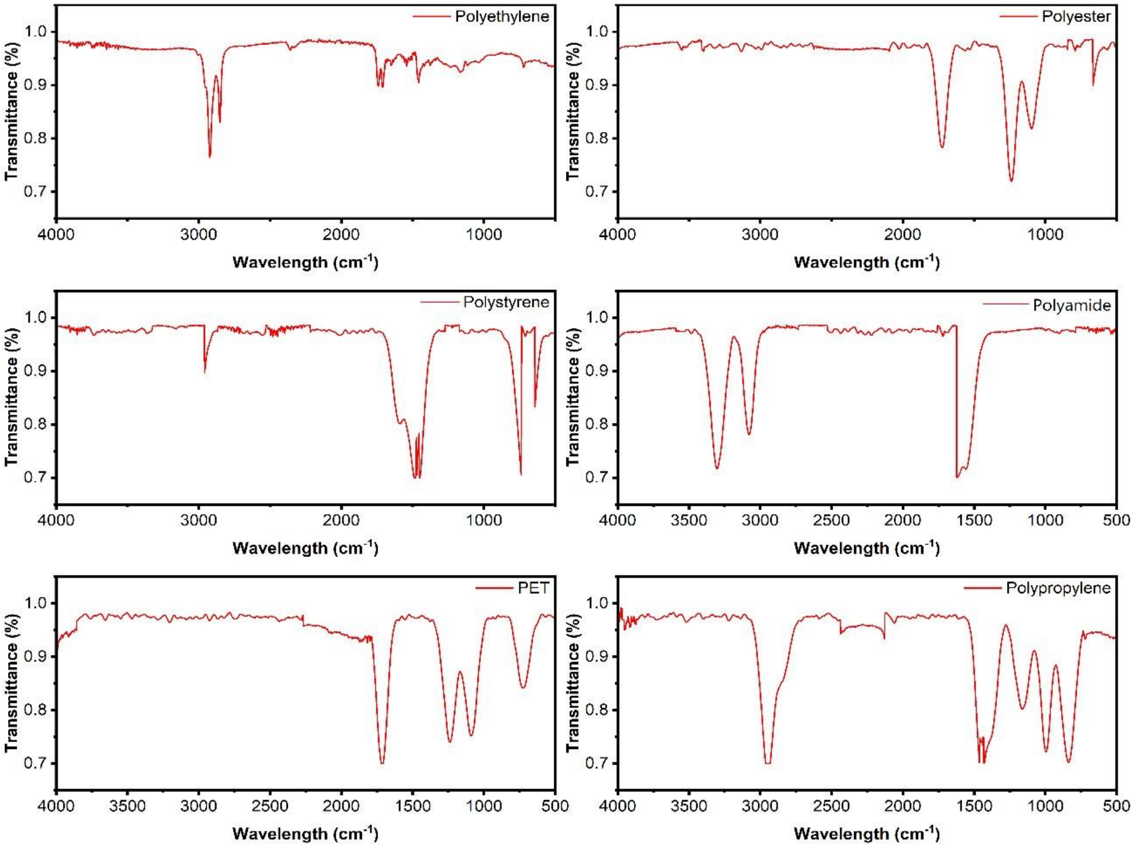


Figure 5.4: FTIR Spectra for the MPs from the Lake Volta

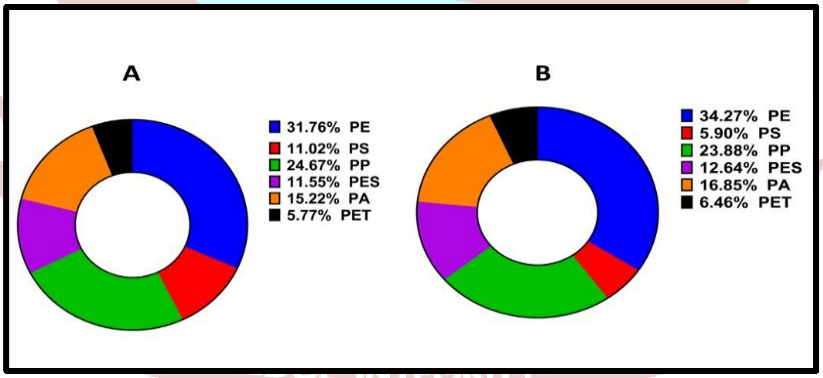


Figure 5: Distribution of MPs in Surface Water (A) and Sediment (B) from Lake Volta based on their polymer types (Note: PE -Polyethylene, PS – Polystyrene, PP – Polypropylene, PES – Polyester, PA -Polyamide and PET- Polyethylene Terephthalate)

5.3.3. Risk Assessment of MPs

The ecological risk assessment of the samples was conducted using an adapted model (Islam et al., 2023; Sangilidurai et al., 2024). For the surface water samples, the minimum average MPs abundance used in calculating the PLI was 3 MPs/L, while for sediments, it was 27 MPs/kg. This was gotten from averaging the abundance from the triplicates from each sampling station and picking the lowest MP value from a site as minimum baseline value. This was because there was no background data to fall on for such calculations. The calculated PLI, PHI, and ERI values for the surface water samples were 2.09, 14.76, and 30.52, respectively. For sediments, the corresponding values were 2.03, 13.02, and 27.44. Based on the ERI results and the indices in Table 10 and the ubiquitous nature of MPs in the Lake, there seems to be a minor ecological risk posed by the contaminants, however, based on the PLI values, the water is said to be polluted with a hazard level of II and medium risk.

Table 5.3: Ecological Risk Indices and their Categories (Islam et al., 2023; Sangilidurai et al., 2024)

PHI	PLI	ERI	Hazard Level	Risk Category
0 – 1	-	<150	I	Minor
1 – 10	<10	150 – 300	II	Medium
10 – 100	10 – 20	300 – 600	III	High
100 – 1000	20 – 30	600 – 1200	IV	Danger
> 1000	> 30	> 1200	V	Extreme danger

However, it is important to note that the PLI alone is not sufficient to determine the overall risk of pollutants, as it depends solely on MP abundance and not on the polymer types present and their associated hazard scores as captured in Table 5.3. This is demonstrated by a strong positive correlation between PLI and MP abundance in both matrices (Surface Water: r = 0.98, p <0.0001, n = 16; Sediment: r = 0.98, p < 0.0001, n=16). From Panel A in Figure 6, the highest ERI value of 55.55 was observed at site 6D, correlating with MP abundance. However, as shown in Panel B, despite the highest MP abundance being recorded at site 2D, the ERI at site 6D reached 58.94, indicating a highest risk. This therefore affirms that site 6D is the hotspot for MP pollution although the risk is minor since the values in both cases are less than 150 (Table 5.3).

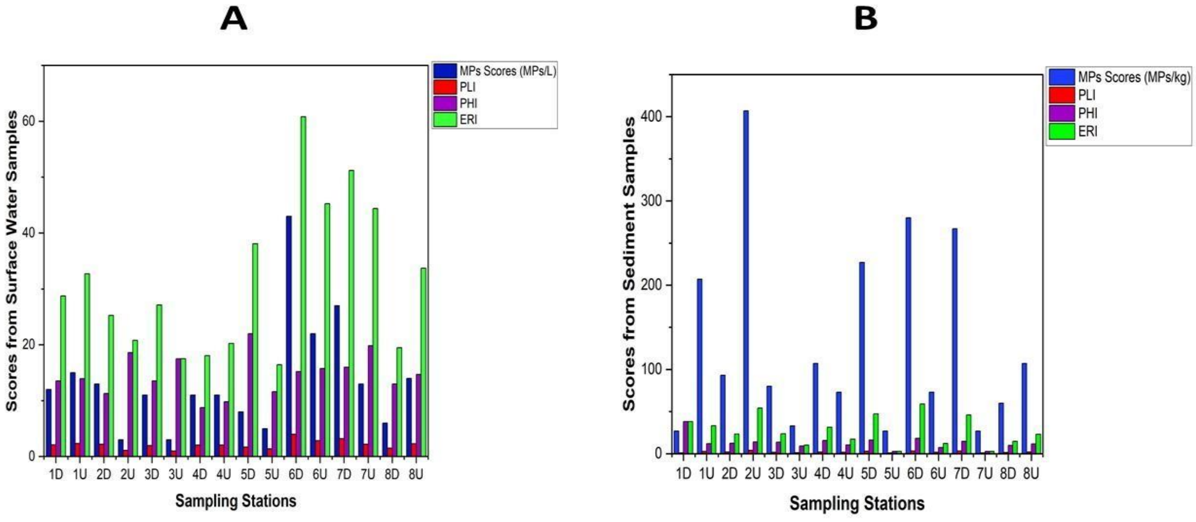


Figure 5.6: Abundance and Ecological Indices in A) Surface water and B) Water sediment samples (Note: PHI-Polymer Hazard Index; PLI-Pollution Load Index and ERI- Ecological Risk Index) from Lake Volta

5.4. Discussion

The laboratory analysis conducted in this study confirmed the widespread presence of MPs in both surface water and water sediment from Lake Volta. These findings align with studies conducted by Shi et al. (2022) and Jain et al. (2024) on Tangxun Lake and Nainital Lake respectively, reporting similar ubiquitous MP contamination. The presence of MPs in all samples from Lake Volta suggests that, like many other freshwater bodies, it is significantly contributing to the global MP pollution crisis, as observed in other studies (Boateng et al., 2024; Egessa et al., 2020; Kumar et al., 2024; Lightman & Moyo, 2024; Mercy et al., 2023; Nava et al., 2023; Tran-Nguyen et al., 2024; Xu et al., 2021). These could be a result of improper management of fishing gear, poor solid waste management, and other anthropogenic activities such as the market days.

In terms of abundance, the significant differences in MPs concentration in the watersediment and surface water matrices suggests differential accumulation and retention behaviours across the lake. This is supported by earlier studies (Ding et al., 2022; Lightman & Moyo, 2024). The high abundance of MPs in sediment reflects the tendency for MPs to settle and accumulate in freshwater ecosystems, which is consistent with similar findings in other aquatic environments (Jain et al., 2024; Lightman & Moyo, 2024; Lorenz et al., 2019). The lack of significant differences in MPs concentrations between sampling locations and strata in both water ($\chi^2 = 15.00$, df = 15, $p = 0.451$; $\chi^2 = 9.79$, df = 7, $p = 0.201$) and sediment ($\chi^2 = 15.00$, df = 15, $p = 0.451$; $\chi^2 = 2.89$, df = 7, $p = 0.895$) suggests that MPs are spread fairly evenly throughout the research area. This may result from widespread and ongoing sources of pollution, such as careless plastic disposal, fishing activities, and market waste, which impact all areas similarly. Additionally, natural processes like water flow, sediment mixing, and current-driven movement likely help maintain this even distribution of particles. The uniformity observed might also be influenced by the amount and timing of sampling, as sampling in just one season may not reflect changes over time or due to specific events. However, the Kruskal-Walli's test confirming a statistically significant variation ($\chi^2 = 20.84$, df =1, $p < 0.0001$), validated by

Dunn’s post-hoc test (mean rank difference = -15.13, $z = -4.56$, $p < 0.0001$) indicating that sediment acts as the study area's main sink for MPs. This pattern aligns with existing research, which shows that sediments often serve as long-term sinks for MPs because of gravitational settling, hydrodynamic conditions, and interactions with particles (Akdogan et al., 2023; Lorenz et al., 2019). The relatively lower concentrations in water may indicate a temporary distribution affected by currents, wind, and seasonal runoff. These findings emphasise the importance of benthic environments in capturing MPs. They also highlight the need for monitoring and management strategies that focus on sediments in freshwater ecosystems like those around Lake Volta.

The spatial distribution analysis of MPs across different strata revealed notable hotspots in strata SII (2U), SVI (6D), and SVII (7D), which exhibited high abundance in both surface water and sediment. The downstream communities, in particular, showed higher levels and greater variability, indicating a greater accumulation of MPs as water flows through the lake system (Dalu et al., 2023; Zhao et al., 2023). This may be attributed to the disparity in waste management regimes, high anthropogenic activities (such as market days), and uneven geographical distribution of the number of plastics entering the lake from the land, resulting from poor drainage engineering systems in some of these sampling locations (Reineccius & Waniek, 2024). The finding also aligns with previous studies suggesting that MPs tend to accumulate in downstream areas due to the transport and deposition of plastics from upstream sources (Dalu et al., 2023; Zhao et al., 2023). These observations highlight the importance of addressing pollution control measures not just at localised hotspots but also across the entire lake to effectively mitigate the spread of MPs.

The predominant type of MP identified in surface water and sediment was fibre, with fibres constituting 97% of MPs in surface water and 77% in sediment. As summarised in Table 5.4, the findings of this study identifying fibres as the dominant shape of MPs in the aquatic environment are consistent with most reports (Boateng et al., 2024; Ghayebzadeh et al., 2021; Tran-Nguyen et al., 2024; Xu et al., 2021), except for the works by Egessa et al. (2020) and Yoon et al. (2024), which present differing results. The disparity might be resulting from the fact that Lake Volta is a stagnant reservoir with higher sedimentation and hence more fibrous MPs. Lakes with strong currents and turbulence, like Uiam Lake, facilitate the transport of larger plastic pieces, increasing fragmentation over time. Additionally, several other papers have found fibres as the dominant MP shapes in either water or sediment samples (Anagha et al., 2023; Zhao et al., 2023). The findings also support earlier work by Boateng et al. (2024) on the lake, supporting the claim that the high fibre abundance may result from fishing activity within the area from lost fishing ropes, nets, cages, and lines. Additionally, fibrous MPs may be more prevalent in the lake due to aquaculture practices that use fishing nets and other materials, as well as weathering of abandoned fishing gear such as nets, lines, and ropes (Anagha et al., 2023).The cooccurrence of fibres with other MP types, such as fragments and films, suggests potential interaction or fragmentation processes that may contribute to the overall MP load.

Interestingly, Pellets were found to be less common in this study, aligning with the findings reported by Ramaremisa et al. (2024), and showed weak correlations with other types of MPs, implying a more independent distribution pattern.

Table 5.4: MP Abundance, Characteristics, and Polymer Composition in Lakes across Different Countries

Lake and Country	Environmental Matrix	Abundance of MPs		Dominant Shapes, Colour and Sizes	Dominant Polymer	References
		Surface Water	Sediment			
Lake Volta (Ghana)	Water and Sediment	15.875 ± 10.69 MPs/L	148.333 ± 119.35 MPs/kg	Fibre, Black, 501–1000 µm	PE, PP	Current Study
Lake Volta (Ghana)	Sediment	-	398 particles per 1.5kg	Microfibre, 1001–3000 µm size	PE, PP	Boateng et al. (2024)
Dhanmondi, Gulshan, and Hatir Jheel lake (Bangladesh)	Water and Sediment	36items/L, 33 items/L, and 19 items/L	29items/kg, 67 items/kg, and 48 items/kg	film,fibre,Transparent, <100 µm	HDPE, LDPE	Mercy et al., (2023)
Gehu Lake (China)	Water	6.33 ± 2.67 n/L	-	Fiber, Transparent, 0.1 – 0.5 mm	PES, Man-made fiber	Xu et al. (2021)
Chilika Lake (India)	Sediment	-	440 ± 3.53 particles/kg (wet)	Fibre, black, 50–500 µ m	HDPE, PS	Kumar et al. (2024)
Lake Victoria (Uganda)	Water	120,588 particles/km^2	-	Fragments, white/transparent, 0.3 – 0.9 mm	PE, PP	Egessa et al. (2020)
Urban lakes (Vietnam)	Water	2145.2 ± 322.6 items/m^3	-	Fibre, white, 500 to 2000 µm	PP, PE	Tran-Nguyen et al. (2024)
Uiam Lake (South Korea)	Water	200–15400 n/m^3	-	Fragment, fibrous, 10 – 100 µm	PMMA, PP	Yoon et al. (2024)

The colour distribution of MPs exhibited a predominance of black MPs in surface water and blue MPs in sediment, reflecting variations in polymer composition, buoyancy, and environmental interactions. Black MPs, primarily composed of low-density polymers such as PE and PP, remain suspended in the water column due to their buoyant nature and are more susceptible to UV-induced degradation and fragmentation. Their widespread presence may be linked to the indiscriminate disposal of polyethylene carrier bags, particularly during market activities, and inefficient waste management systems that facilitate their transport into the lake (Egessa et al., 2020; Ramaremisa et al., 2022). In contrast, blue MPs, predominantly composed of higher-density polymers such as polyester from textiles, fishing nets, and synthetic ropes, are more likely to settle and accumulate in sediments due to their greater density and resistance to photo degradation in low-light conditions. Furthermore, biofilm formation can alter the visual properties of MPs, with surface particles undergoing color modification, whereas sediment MPs retain their original coloration due to reduced environmental exposure. These findings suggest that the spatial distribution of MP colors is governed by polymer-specific properties, hydrodynamic sorting, and anthropogenic inputs, shaping their accumulation patterns in different environmental matrices.

The size distribution of MPs further revealed that larger MPs (>1000 µm) were more abundant in surface water, while sediment contained a higher proportion of smaller particles in the range of 501–1000 µm. This is because smaller MPs have a higher tendency to sink than larger ones(Liu et al., 2022b). Boateng et al. (2024) previously identified MPs in the 1001–3000 µm size range as the dominant class in sediment. This finding contrasts with the size distribution observed in sediment in this study but aligns with those found in surface water. The variation may be attributed to differences in MP degradation rates, influenced by temperature variations, as the northern part of the lake is warmer than the southern region (Gebrechorkos et al., 2022).

Polymer identification through FTIR spectroscopy revealed that PE was the most prevalent polymer type in both surface water and sediment samples, followed by PP, PS, and PES.

The dominance of PE and PP is consistent with findings from other aquatic studies by Egessa et sal. (2020), Reineccius & Waniek (2024) and Tran-Nguyen et al. (2024). These polymers are widely used in packaging, fishing, irrigation activities and other consumer products, making them common contaminants in freshwater systems. The result also supports the earlier finding of having black-coloured MPs in abundance. Identifying these polymers highlights the need for targeted efforts to reduce plastic waste, particularly in urban areas that are major sources of such pollution. Furthermore, the dominance of these two polymers aligns with the predominant colours identified earlier.

The indices indicate that the lake's surface water is subject to a greater pollutant load and slightly higher associated hazards and risks compared to its sediments. Specifically, the surface water's PLI of 2.09 versus 2.03 in sediments suggests a more significant accumulation of contaminants in the water column, likely due to direct pollutant inputs such as runoff. Moreover, the PHI and ERI values—14.76 and 30.52 for surface water compared to 13.02 and 27.44 for sediments—imply that although both matrices are at risk, the exposure and potential adverse impacts on aquatic life and human health are marginally higher in the surface water. Based on the MP's polymer types with PHI values of 14.76 for surface water and 13.02 for sediments (hazard level III) in both cases, which is far less than the PHI values (>1000) recorded by Ranjani et al. (2021).

5.5. Environmental and Policy Implications

There are major environmental and policy ramifications to Lake Volta's high MP contamination, which is demonstrated by the particles' widespread presence in both surface water and sediments. Since MPs can interact with other pollutants, bioaccumulate in aquatic creatures, and perhaps upset food webs, their build-up poses a major environmental concern to aquatic ecosystems and human health. This is especially true of fibres. The identification of contamination hotspots and spatial variability, particularly in downstream areas, suggests that local sources including market activity, urban runoff, and poor waste management techniques may be important contributors to the pollution load. From a policy perspective, these findings underscore the urgent need for improved plastic waste management, stricter enforcement of pollution control measures, and the implementation of sustainable practices such as bioremediation and the use of environmentally friendly materials. Furthermore, given Lake Volta's transboundary nature—cutting across six countries—there is a pressing demand for regional collaboration and harmonised policies to effectively mitigate MP pollution and safeguard the lake's ecological integrity and its vital socio-economic benefits, including aquaculture and community livelihoods. The Environmental Protection Agency's initiative to ban single-use plastics in Ghana is a positive step, but a suitable alternative will be necessary.

5.6. Conclusion

This study has provided crucial insights into the abundance, distribution patterns, and characteristics of MPs in the surface water and sediments of Lake Volta. The widespread presence of MPs, particularly the dominance of fibres, highlights the growing environmental concerns associated with plastic pollution in freshwater ecosystems. The spatial distribution analysis identified MP hotspots in strata SII (2U), SVI (6D), and SVII (7D), with higher accumulation in downstream communities due to disparities in waste management, urbanization-driven anthropogenic activities, and the transport of plastics from upstream sources. The findings also emphasise that sediment acts as a major sink for MPs, reinforcing the need for a holistic approach to addressing plastic pollution across different environmental matrices. The ecological risk assessment further underscores the potential hazards posed by MPs to aquatic life and human health, with surface water presenting a slightly greater risk due to its higher pollutant load.

Lake Volta's critical role in regional fisheries, aquaculture, and local livelihoods necessitates targeted mitigation strategies and policy interventions to address MP pollution, whose long-term ecological and health impacts, including interactions with other pollutants and bioaccumulation in aquatic organisms, require further investigation. Given its transboundary nature spanning six countries, collaborative regional efforts and expanded research across Ghana and neighboring nations are essential for a comprehensive understanding of pollution patterns. Implementing sustainable waste management practices, enhancing public awareness, exploring nature-based solutions such as bioremediation, replacing single-use plastics with biodegradable alternatives, and adopting hydrodynamic approaches to assess seasonal variations in MP loads are crucial steps toward preserving Lake Volta's ecological integrity and ensuring its continued socioeconomic benefits.

The study recommends that future research on MP contamination in sediments should explore normalization approaches that account for sediment characteristics. Specifically, normalizing MP abundance to parameters such as organic carbon content, grain size, mineral markers like aluminum or iron oxides, or expressing concentrations per unit dry weight or total mass, could enhance comparability and interpretability of findings. Additionally, to improve the recovery of denser polymers such as PET and polyvinyl chloride (PVC), it is advised that future studies consider using higher-density salt solutions—such as sodium iodide (NaI) or zinc chloride ($ZnCl_2$)—for density separation.

The sodium chloride (NaCl) solution employed in this study, while accessible and less hazardous, may have led to an underestimation of heavier MP fractions due to its lower density. Finally, future research could consider the receding water level (rainy season) to ascertain the differences in the MP loads as captured in the present work.

5.7. Bridging to Chapter 6: From Environmental Contamination to Biological Uptake

This chapter has established that Lake Volta's water column and benthic sediments contain measurable microplastic pollution, with identifiable hotspots in areas of high human activity. The presence of MPs in the environment creates direct exposure pathways for aquatic organisms. Given Lake Volta's critical role as Ghana's primary inland fishery, the ingestion of MPs by fish represents a key transfer mechanism of pollution into the aquatic food web, with implications for both ecological health and human food safety. To assess this biological uptake and understand the progression of risk from environment to organism, Chapter 6 investigates the abundance, characteristics, and bioaccumulation patterns of microplastics in two key commercial fish species: tilapia (cichlid family) and catfish (clarias family).

CHAPTER SIX

Distribution and Abundance of Microplastics in Tilapia and Catfish Species in Lake Volta, Ghana

Abstract

The global proliferation of microplastics (MPs), largely resulting from poor plastic waste management, is raising increasing concerns, particularly within freshwater habitat that remains understudied. This study looks at the presence and properties of MPs in the gastrointestinal tracts and gills of tilapia and catfish species from Lake Volta, Ghana. A total of 96 fish specimens, representing 11 species (five tilapia and six catfish), were analysed from 16 communities around Lake Volta. MPs were extracted through alkaline digestion and analysed visually, microscopically, and with μ-FTIR spectroscopy. A total of 229 MP particles were detected. The average MP per fish for tilapia was 2.47 ± 1.30 and catfish was 2.29 ± 1.73. Normalised to body weight, tilapia concentrations were 0.07 ± 0.08 MPs/g, while catfish concentrations were 0.06 ± 0.07 MP/g. MPs less than 100 μm were predominant, particularly those under 50 μm and between 51-100 μm. The most prevalent shape was fibre, and the primary colour was black, most likely due to the abundance of polyethylene (PE) polymers. While fish total length and body weight were strongly associated, fish size and condition factors had no significant relationship with MP ingestion. The Mann-Whitney test indicated that there was no significant relationship between fish type and MPs load ($U = 412$, $p = 0.44$, rank-biserial correlation $r = 0.08$). The results also show that waterborne microplastics were the dominant exposure route, with tilapia accumulating more than catfish, highlighting species-specific uptake and localised contamination hotspots. These findings demonstrate the existence of MPs in freshwater fish species within Lake Volta, emphasising the urgent need for more ecological and human health risk studies of MPs in freshwater lake fisheries.

6.1. Introduction

Plastic pollution has emerged as a significant global environmental issue, with plastic production surging from 1.5 million metric tons in 1950 to 413.8 million metric tons in 2023 (Claessens et al., 2011; Cowger et al., 2024a; Nasrabadi & Bonyadi, 2025). The widespread use and improper disposal of plastics have led to the proliferation of microplastics (MPs), particles smaller than 5 mm, that now permeate diverse ecosystems (Amponsah et al., 2024; Andoh et al., 2024). These contaminants have been detected in remote locations, from the Mariana Trench to Mount Everest, underscoring their pervasive nature and growing ecological footprint (Anagha et al., 2023). While MPs are ubiquitous across terrestrial, freshwater, and marine environments, their presence in water bodies intensified during the COVID-19 pandemic due to increased plastic waste generation (Han et al., 2024). The far-reaching consequences of MP pollution have sparked global concern over its potential environmental and human health risks.

In marine systems, MPs are extensively transported by ocean currents, accumulating in surface waters, sediments, and deep-sea ecosystems (Bergmann et al., 2015). Their ingestion by marine organisms poses serious ecological threats, as they can act as vectors for toxic chemicals, disrupt physiological functions, and alter the dynamics of food webs (Andoh et al., 2024). Moreover, the bioaccumulation of MPs in seafood raises concerns about human exposure through consumption. (Bhuyan, 2022; Woh et al., 2024). While marine environments, according to (Christensen et al., 2020), and (Rochman, 2018) have been extensively studied, freshwater systems are increasingly recognised as critical reservoirs and transport pathways for MPs (Adu-Boahen et al., 2020; Guo et al., 2024).

MPs persist in lake water columns, accumulate in sediments, and are ingested by aquatic organisms, yet their long-term effects remain poorly understood (Barceló et al., 2023; Kumar et al., 2021; Mercy et al., 2023; Nuamah et al., 2022). Contamination of freshwater fish species by MPs remains underexplored unlike to the marine environments. Additionally, research gaps persist in assessing ingestion rates, bioaccumulation, and toxicological effects of MPs in lake fish (Awewomom et al., 2024). The lack of standardadised methodologies for MP sampling, extraction, and chemical characterisation further complicates data comparability across studies (Reineccius & Waniek, 2024). The major sources of MP pollution in lakes, including domestic waste, fishing activities, agricultural runoff, and atmospheric deposition, are poorly characterised, particularly in Lake Volta (Bruce-Vanderpuije et al., 2025). Understanding these sources and transport pathways is essential for designing effective mitigation strategies. Given the intricate interactions between environmental factors and MP distribution, there is an urgent need for comprehensive investigations into their presence and ecological impacts across both marine and freshwater ecosystems.

Lake Volta, one of the world's largest artificial reservoirs and a vital freshwater resource in Ghana, supports regional fisheries, agriculture, and domestic water needs. (Acquah et al., 2021; Boateng et al., 2024). Its expansive network sustains both aquatic biodiversity and the livelihoods of local communities. However, increasing pollution, including the influx of MPs, poses significant threats to the lake's ecological balance and human health. (Boateng et al., 2024). According to the FAO 2016 report, Lake Volta hosts approximately 140 fish species. The dominant landings include *Chrysichthys* spp. (Catfish) at 34.4%, followed by *Oreochromis* spp. (Tilapia) at 28.1%, *Synodontis* spp. at 11.4%, and *Labeo* spp. at 3.4%. Other notable species include *Mormyrops* spp. (2.0%), *Heterotis* niloticus (1.5%), Clarias spp. (1.5%), *Schilbe* spp. (1.4%), *Odaxothrissa* mento (1.4%), *Bagrus* spp. (1.35%), and *Citharinus* spp. (1.2%). The remaining species, each comprising less than 1% of the total catch, include *Alestes* spp., *Brycinus* spp., *Distichodus* spp., *Gymnarchus* spp., *Hydrocynus* spp., and *Lates* niloticus (Doku et al., 2018; FAO, 2016)

The condition or well-being of species of Tilapia and Catfish, are key indicators of aquatic health. Given their widespread economic and ecological significance, including consumption and presence in the lake accessing the extent of MP contamination in these fish species is crucial for understanding potential risk to food security and towards achieving sustainable development goal 3 (good health and well-being). The ingestion of MPs by fish has cascading effects on growth, reproduction, and overall survival, yet data on their occurrence in Lake Volta's fish populations remain limited (Acquah et al., 2021; Boateng et al., 2024). Seasonal hydrodynamic patterns and lake morphology could further influence MP distribution, but limited studies have been conducted to assess these dynamics in such an important freshwater (Boateng et al., 2024; Bruce-Vanderpuije et al., 2025). Understanding these factors is critical for identifying high-risk zones within the lake and informing targeted pollution control measures.

To address these knowledge gaps, this study focuses on three primary objectives: (1) determine the presence and concentration of MPs in the gastrointestinal tracts and gills of Tilapia and Catfish from Lake Volta, (2) characterise the physical and chemical properties, size, shape, colour, and polymer types, of the MPs found in these species, and (3) assess the relationship between fish size and condition factors and MP ingestion loads. By generating scientifically robust data on MP contamination in Lake Volta's fish populations, this research will contribute to the global understanding of freshwater MP pollution, inform policy interventions, and support sustainable fisheries management in Ghana and beyond.

6.2. Materials and Methods

6.2.1. Study Area and Fish Sampling

Fish samples used in this study were collected from Lake Volta (Figure 6.1) for microplastic analysis. Lake Volta, a reservoir created primarily for hydropower generation, extends over 400 km (250 miles) with a surface area of 8,502 km² (3,283 miles²). The lake supports approximately 140 fish species and sustains extensive fishing activities (FAO, 2016). The proliferation of fishing communities along its banks has led to the development of market centres, where poor waste management regimes contribute to significant plastic pollution.

Fish samples were collected in January 2024, coinciding with rising water levels. Fish specimens were collected from sixteen (16) fishing communities across the eight (8) fisheries data collection strata designated by the Food and Agriculture Organization (FAO)(FAO, 2016) (Figure 6.1 & Table 6.1):

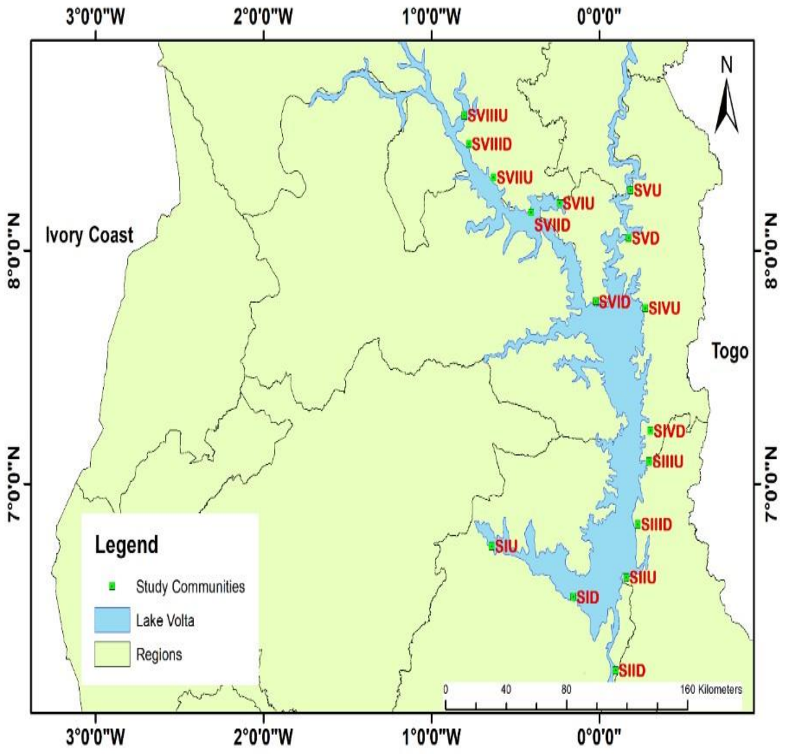


Figure 6.1: Map of Lake Volta showing the sampling communities (Note: U=Upstream, and D= Downstream: SI to SVIII represent stratum 1 to 8)

Table 6.1: Details of Sampling Communities and their Coordinates

Strata	**ID**	**Sampling Community**	**Region**	**Coordinate**
1	SID	Akateng	Eastern	6° 31’ 2.8266” N, 0° 9’ 16.6284” W
	SIU	Kotoso	Eastern	6° 44’ 3.9516” N, 0° 38’ 26.5308” W

2	SIID	Atimpoku	Eastern	6° 12’ 12.2466” N, 0° 5’ 46.0752” E
	SIIU	Dzemeni	Volta Region	6° 36’ 7.1886” N, 0° 9’ 37.1376” E
3	SIIID	Kpebe	Volta Region	6° 49’ 42.7404” N, 0° 13’ 43.2372” E
	SIIIU	Dafor Tornu	Volta Region	7° 5’ 47.6082” N, 0° 17’ 47.2662” E
4	SIVD	Odormitor	Oti Region	7° 13’ 37.7904” N, 0° 18’ 13.9788” E
	SIVU	Ayirefie Battor	Oti Region	7° 45’ 10.71” N, 0° 16’ 24.9204” E
5	SVD	Dambai	Oti Region	8° 3’ 15.5838” N, 0° 10’ 25.1904” E

	SVU	Kitari	Northern Region	8° 15’ 28.7454” N, 0° 11’ 9.6648” E
6	SVID	Kete-Krachi	Oti Region:	7° 46’ 53.4606” N, 0° 1’ 19.0662” W
	SVIU	Grubi	Oti Region	8° 12’ 5.961” N, 0° 14’ 13.2288” W
7	SVIID	Lonto	Northern Region	8° 9’ 40.6002” N, 0° 24’ 21.7944” W
	SVIIU	Makango	Savannah Region	8° 18’ 46.1298” N, 0° 37’ 51.819” W
8	SVIIID	Kafaba No. 2	Savannah Region	8° 27’ 22.035” N, 0° 46’ 36.5916” W
	SVIIIU	Accrape	Savannah Region	8° 34’ 42.3264” N, 0° 48’ 13.4238” W

Fish sampling was carried out with the assistance of contracted fishermen using various fishing nets and basket traps. At each sampling site, five tilapia and five catfish of varying sizes were collected, giving a total of 160 fish (80 tilapia and 80 catfish). From each set of five, three individuals were selected for analysis, while two were reserved as backups to replace any specimens lost or compromised during dissection. Thus, 96 fish (48 tilapia and 48 catfish) were ultimately processed for microplastic analysis. The collected specimens were immediately rinsed with distilled water, stored on ice, and temporarily stored in a refrigerator at 4 °C for up to 48hrs before transported to the Fishery and Aquaculture Laboratory of the Council for Scientific and Industrial Research – Water Research Institute (CSIR-WRI), Ghana, for further processing and analysis. A handheld Garmin GPSMAP 67i Global Positioning System (GPS) with an accuracy of ± 3.65 meters, manufactured in Taiwan, was used to record coordinates right after sampling to help with the spatial modelling (Ghansah et al., 2022).

6.2.2. Fish Digestion and Extraction

Of the samples collected, 96, that is 3 tilapia and 3 catfish per site were utilised for this study. The selected fish samples were thawed at room temperature (~30 °C) before analysis. Fish species were identified with keys of Dankwa et al. (1999) and Paugy et al. (2003). Morphometric measurements, including body weight (BW) (wet weight), total length (TL), and standard length (SL), were recorded following the protocol described by Adeogun et al. (2020) to estimate the condition factor (K) of each specimen. The condition factors were calculated using Fulton's condition factor formula (6.1).

$$K = \frac{100\ \mathrm{BW}}{\mathrm{TL}^3} \qquad (6.1)$$

The fish specimens were dissected using sterilised scissors and a scalpel, and the gastrointestinal tracts (and gills) were excised, cut into smaller sections, and placed in clean glass bottles with secure covers, (Piyawardhana et al., 2022). Tissue digestion was performed using 20 mL of 10% potassium hydroxide (KOH) solution, with the samples left to digest for 72 hours (Hara et al., 2020) To eliminate any saponification byproducts, 10 mL of 100% ethanol was added to the digestate. The resulting solution was then subjected to mechanical agitation for 3 hours at 300 rpm using a KS 501 digital orbital shaker (IKA-Werke GmbH & Co. KG, Germany) at the Chemistry Laboratory of CSIRWRI, Ghana (Figure 6.2). The extracts were subsequently filtered through 1.2 µm microfiber filtres, which were placed in Petri dishes covered with aluminum foil and dried at 60 °C for 24 hours before microscopic examination.

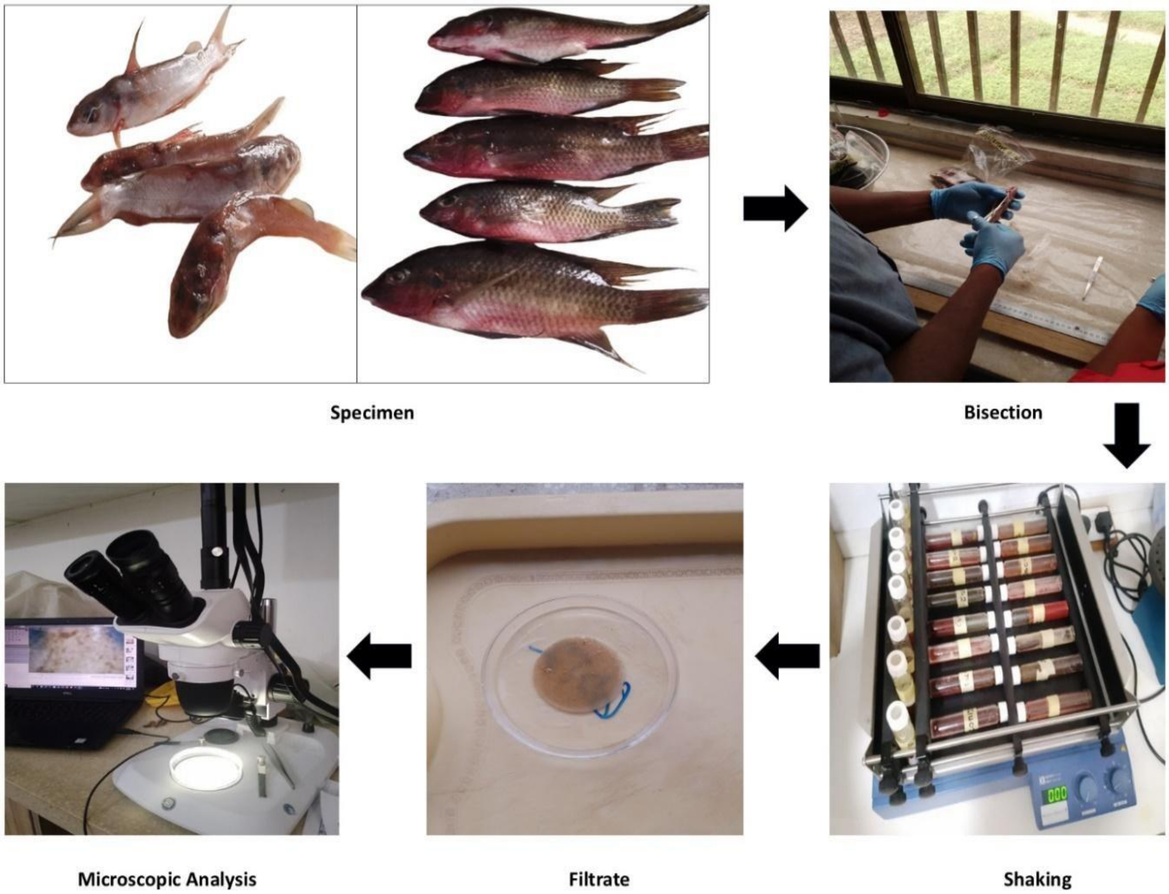


Figure 6.2: Microplastic Identification Processes

6.2.3. MP quantification and identification

The filtered extracts were examined under the microscope Nexiuszoom tinocular microscope and SZ61; Olympus, Hamburg, Germany. Identified MPs were then counted and categorised based on their morphological type (e.g., fragments, fibres, pellets, films, and other forms such as foam or beads), colour classification (blue, clear, black, and additional colours including yellow and green), and size distribution (≤50 µm, 51–100 µm, 101–500 µm, 501–1000 µm, and 1001–5000 µm) according to the criteria outlined by Boateng et al. (2024).

The suspected MP samples underwent characterisation to confirm their polymer composition and inclusion in the analysis. A Compact FT-IR spectrometer ALPHA II (Bruker Nano GmbH, Berlin, Germany) at the Materials Science and Engineering Laboratory, University of Ghana was employed for polymer identification. Each sample was clamped onto the diamond crystal and scanned 32 times in transmittance mode over a wavenumber range of 400–4000 cm^{-1} at a resolution of 4 cm^{-1}. The collected spectra were processed and plotted using the OriginPro software version 2025 developed by OriginLab Corporation (USA), then systematically compared against reference databases and existing literature for polymer classification (Cowger, et al., 2024b; Hossain et al., 2023a; Primpke et al., 2018; Rianda et al., 2020).

6.2.4. Estimation of Bioaccumulation

Data on sediment and surface water from the earlier study presented in Chapter Five were used for this analysis. Additionally, fish samples collected in the current study were analysed for whole-organism MP content. To account for differences in body size, raw MP counts (items/individual) were normalised to body weight, following procedures outlined in previous studies (Expósito et al., 2022; Hossain et al., 2023b). The normalised concentration was calculated as (Equation 6.2):

$$C_{fish}\ (MPs/kg) = \frac{MPs\ in\ fish}{Fish\ weight\ (kg)} \qquad (6.2)$$

Bioaccumulation was evaluated using two indices (Equation 6.3 and 6.4) (Savoca & Pace, 2021):

i) Bioaccumulation Factor (BAF):

$$BAF\ (L/kg) = \frac{C_{fish}\ (MPs/kg)}{C_{water}\ (MPs/L)} \qquad (6.3)$$

ii) Biota-sediment Accumulation factor (BSAF):

$$BSAF = \frac{C_{fish}\ (MPs/kg)}{C_{sediment}\ (MPs/kg)} \qquad (6.4)$$

Site-level concentrations of MPs in water and sediment were derived as mean values of the triplicate measurements reported by (Andoh et al., 2025b), and used as representative environmental baselines. By comparing relative magnitudes of BAF and BSAF, the predominant exposure pathway was inferred: BAF > BSAF indicates waterborne uptake, whereas BAF < BSAF suggests sediment-associated exposure (Savoca & Pace, 2021).

6.2.5. Data Analysis

The data was analysed using OriginPro software (version 2025). The normality of the data distribution was checked using the Shapiro-Wilk normality test before other statistical tests were performed. Statistical tables and descriptive statistics such as the median, standard deviation, interquartile range and standard error were used to describe the data. As a result of none normality nature of the data a Spearman correlation was employed to characterise the relationship between the total length, average body weight (wet weight) and condition factors of individual fish and their corresponding average microplastic load (Piyawardhana et al., 2022). Spearman's correlation was also employed to make inferences about the fish size, condition factor and the MPs load. Mann-Whitney test was employed to hypothesise the relationship between fish type and MPs load. At $p < 0.05$ ($\alpha = 5\%$), all results were considered statistically significant.

To better understand the potential biological determinants of microplastic (MP) ingestion in freshwater fish, this study examined the relationship between MP abundance and key morphometric indicators—namely, fish size (length and weight) and condition factor (CF). Fish size is often considered a proxy for age and feeding capacity, which could influence exposure to MPs over time. Similarly, the condition factor reflects the overall health and nutritional status of fish and may be impacted by the ingestion of non-nutritive particles such as MPs.

Accordingly, the following hypotheses were formulated and tested:

Fish size and MPs ingestion

Null hypothesis ($\mathbf{H_0}$): There is no significant relationship between fish size and MP ingestions

Alternative hypothesis ($\boldsymbol{H_1}$): There is a significant relationship between fish size and MP ingestions

Condition Factor and MPs ingestion

Null hypothesis ($\mathbf{H_0}$): There is no significant relationship between condition factor and MP ingestions

Alternative hypothesis ($\boldsymbol{H_1}$): There is a significant relationship between condition factor and MP ingestions

Fish Type and MPs ingestion

Null hypothesis ($\mathbf{H_0}$): There is no significant relationship between fish type and MP ingestions

Alternative hypothesis ($\boldsymbol{H_1}$): There is a significant relationship between fish type and MP ingestions

6.2.6. Quality Control

To prevent contamination of the samples, quality control methods prescribed by Belontz & Corcoran, (2021) and Xiong et al. (2024) were employed. During the sample collection stage, all collected samples were first washed thoroughly in the lake and wrapped in aluminum foil and then kept in laboratory specimen transport bag and transported to the laboratory on ice. Additionally, all glasswares used in the laboratory were decontaminated with 10% nitric acid for 24 hours, and thoroughly rinsed using distilled water. Fish specimens were padded to get rid of any oily content before dissection.

6.2.7. Ethical Clearance

Ethical approval was needed since fish samples were used in this study. Ethical clearance was provided by the Ethics Review Committee of the University of Energy and Natural Resources (UENR), with the approval document provided at Appendix I. Additionally, before the commencement of fieldwork, permission was sought and obtained from relevant local authorities, including traditional leaders, Assembly members, Unit Committee members, and other key stakeholders to ensure community engagement and compliance with local governance protocols.

6.3. Results

6.3.1. Microplastic Abundance in Fish

A total of 96 freshwater fish specimens (48 tilapia and 48 catfish) were analysed, comprising five tilapia species and six catfish species. Tilapia showed a wide range of habitat preferences, from pelagic (*Hemichromis fasciatus*), benthopelagic (*Oreochromis niloticus* and *Sarotherodon galilaeus*), and mid-water benthic (*Chromidotilapia guntheri*) zones to completely benthic zones (*Coptodon zilli*) (Table 6.2).

However, except for *Synodontis sorex*, which lived in benthopelagic environments, catfish, including *Bagrus docmak* and several *Chrysichthys* species, were primarily benthic. Most species have omnivorous feeding habits (Table 6.2).

Table 6.2: Comprehensive summary of biometric, ecological, and microplastic (MP) ingestion data

	Species	**Habitats**	**Trophic habit**	**TL (cm)**	**W (g)**	**Average MPs**	**Number of MPs / species**	**K**	**N**
Tilapia	*Chromidotilapia guntheri*	Mid-water benthic	O	10.5	21.64	0	0	1.87	1
	Oreochromis niloticus	Benthopelagic	O	14.8	83.01	5	5	2.56	1
	Hemichromis fasciatus	pelagic	C	10.1±0.5	15.77 ± 3.4	3.50 ± 0.7	7	1.54 ± 0.1	2
	Sarotherodon galilaeus	Benthopelagic	O	16.7±4.1	127.99±67.1	2.00 ± 0.9	24	2.46 ± 0.3	12
	Coptodon zilli	Benthic	H	13.4±3.4	56.83±40.2	2.59 ± 1.3	83	2.00 ± 0.3	32
Catfish	*Synodontis sorex*	Benthopelagic	O	14.5±0.1	31.07±5.2	2.67 ± 2.9	8	0.11 ± 0.2	3
	Bagrus docmak	Benthopelagic	P	34.7±4.1	220.54±82.3	2.00 ± 0.6	10	0.50 ± 0.1	5
	Chrysichthys auratus	Benthic	O	15.8±1.7	33.48±5.25	1.25 ± 1.0	5	0.86 ± 0.2	4
	Chrysichthys maurus	Benthic	O	17.1±2.3	37.98± 16.9	3.00 ±1.0	9	0.72 ± 0.1	3
	Chrysichthys walkeri	Benthic	O	21.7±2.1	85.21±28.8	1.75 ±1.3	14	0.81 ± 0.1	8
	Chrysichthys nigrodigitatus	Benthic	O	16.8±3.8	42.68±30.1	2.56 ± 2.0	64	0.81 ± 0.1	25

O = Omnivore, C = Canivores, H = Herbivore, P = Piscivore, N = Total number of fish belonging to the specie, TL= Average total length of all fishes belonging to the specie, and W= average weight of all the fishes belonging to the specie

Microplastic (MP) contamination in tilapia and catfish exhibited significant variability throughout sixteen sampling stations, as captured in Figure 6.3, with the highest concentration recorded at Dambai with Station ID SVD, especially in catfish (about 16 particles) compared to tilapia (about 12 particles), and the lowest concentrations (fewer than 6 particles) in Makango (SVIIU), Kafaba No. 2 (SVIIID), and Accrape (SVIIIU). Overall, tilapia ingested somewhat more MPs than catfish at most sites (e.g., Atimpoku (SIID), Dzemini (SIIU), Kotoso (SIU)), indicating that species-specific feeding habits influence exposure. These spatial patterns most likely reflect local pollution sources (e.g., urban runoff) and environmental processes (dilution, sedimentation) that influence MP availability, emphasising the importance of targeted monitoring and management to reduce plastic inputs into freshwater systems.

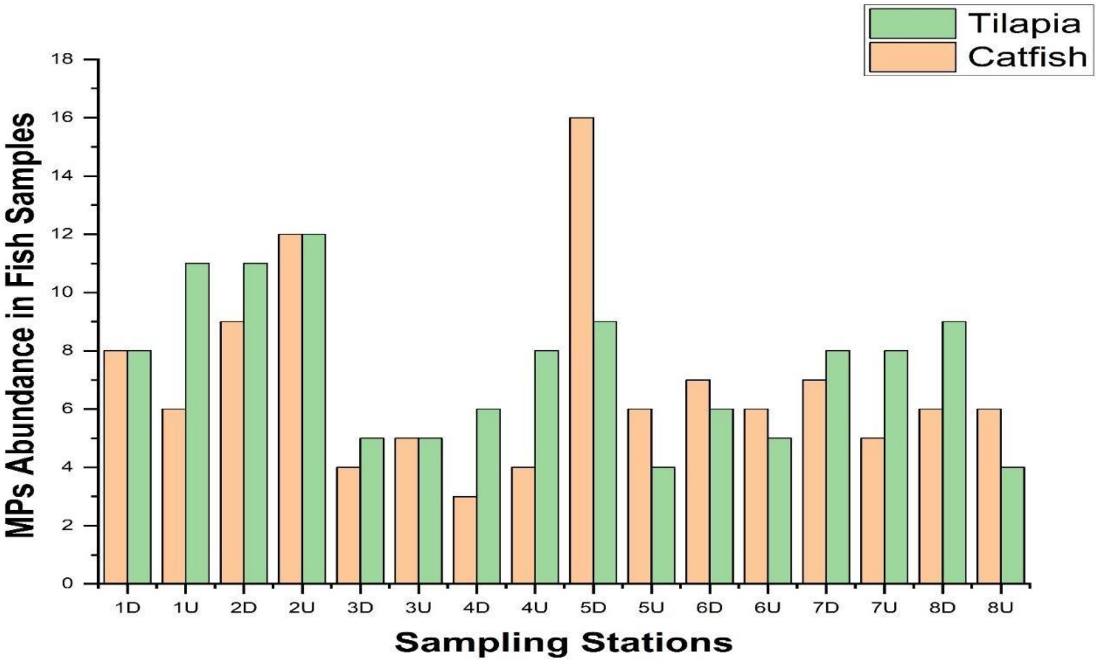


Figure 6.3: Total MPs at each sampling station per fish type

Additionally, a considerable interspecific heterogeneity was found by morphometric analysis. H. fasciatus was the smallest species in terms of size sampled (10.1 ± 0.5 cm;

15.77 ± 3.4 g), and B. docmak was the largest in terms of size (34.7 ± 4.1 cm; 220.54 ± 82.3 g). In general, tilapia species (e.g., O. niloticus: 2.56) had greater condition factor (K), a proxy for somatic robustness, than catfish (e.g., C. nigrodigitatus: 0.81), suggesting that the former were in better physiological condition. Patterns of MP intake also differed by species and ecological niche. The species with the highest average MP loads were C. zilli, H. fasciatus, and C. maurus. Because of their sediment-associated feeding habits, benthic omnivores and herbivores may be more susceptible to MP contamination. Notably, C. zilli had the highest overall MP count (83 MPs from 32 individuals). The Spearman correlation analysis of the number of fish per species and the corresponding MPs retrieved indicates a strong positive relationship. ($r = 0.99$, $p < 0.0001$). This implies that as the number of fish of a particular species increases, the number of MPs also increases, and vice versa.

On average, each fish contained 2.39 ± 1.52 microplastic (MP) particles. When disaggregated by fish types, Tilapia exhibited an average MP load of 2.47 ± 1.30 items per individual, while Catfish had a slightly lower average of 2.29 ± 1.73 items per individual. When normalised to body weight, MP concentrations were 0.07 ± 0.08 items/g for tilapia and 0.06 ± 0.07 items/g for catfish, with an average of 0.06 ± 0.07 items/g. Due to the failure of the Shapiro-Wilk normality test, a non-parametric Mann-Whitney test was employed to assess differences in MP ingestion between the two fish types. The analysis revealed no statistically significant difference ($U = 412$, $p = 0.44$, rank-biserial correlation $r = 0.08$).

In terms of biometric data, tilapia showed a marginally higher average wet body weight (72.72 ± 57.15 g) compared to catfish (66.51 ± 66.57 g). The combined average wet weight across all sampled individuals was 66.61 ± 61.80 g. In contrast, catfish demonstrated a greater average total length (19.3 ± 6.52 cm) than tilapia (14.1 ± 3.80 cm), with the pooled average length for all specimens being 16.67 ± 5.9 cm. Despite their smaller stature, the average condition factor of tilapia was much greater (K = 2.11 ± 0.36) than that of catfish (K = 0.79 ± 0.18). The total average K value for all fish studied was 1.45 ± 0.7. This interspecific variation in condition factor highlights potential variations in environmental adaptability, growth efficiency, and energy absorption. Notwithstanding exposure to microplastic pollution, the higher K values seen in tilapia might indicate improved physiological resilience or more effective energy absorption.

6.3.2. Characteristics of MPs in Biota

Figure 4 comprehensively characterizes MPs in tilapia and catfish samples across various sampling stations, based on size, colour, and shape. Panel A illustrates that MPs smaller than 50 µm were the most dominant across stations, followed by those in the 51–100 µm and 1001–5000 µm ranges. This trend is further supported by Panel B, where tilapia exhibited a higher abundance of MPs in the <50 µm category. The distribution reveals that smaller microplastics (<100 µm) are more prevalent in fish diets, particularly in Tilapia, while larger MPs are still significantly ingested, especially by benthic feeders like Catfish. This underscores the pervasive presence of MPs across all size classes in Lake Volta's aquatic environment. Moreover, the differences in the feeding by fish may reflect speciesspecific feeding strategies or habitat preferences, influencing their exposure to different

MP size classes.

Panels C and D (Figure 6.4) demonstrate that black-coloured MPs were predominant in both species, followed by blue and clear particles, indicating the widespread presence of dark-coloured plastic debris, potentially originating from frequently used domestic singleuse plastics or fishing products. Regarding MP shape (Panels E and F), fibres (microfibres) and films were the most commonly recovered types across stations, regardless of species, pointing to common and persistent sources of plastic pollution in Lake Volta. Catfish showed a higher proportion of fragments, while tilapia exhibited relatively more pellets and "other" shapes. These findings suggest differing ingestion pathways between the two species and highlight a pervasive contamination of freshwater ecosystems by MPs. The observed patterns underscore the ecological relevance of microplastic pollution and the need for targeted interventions to limit plastic waste entering aquatic environments.

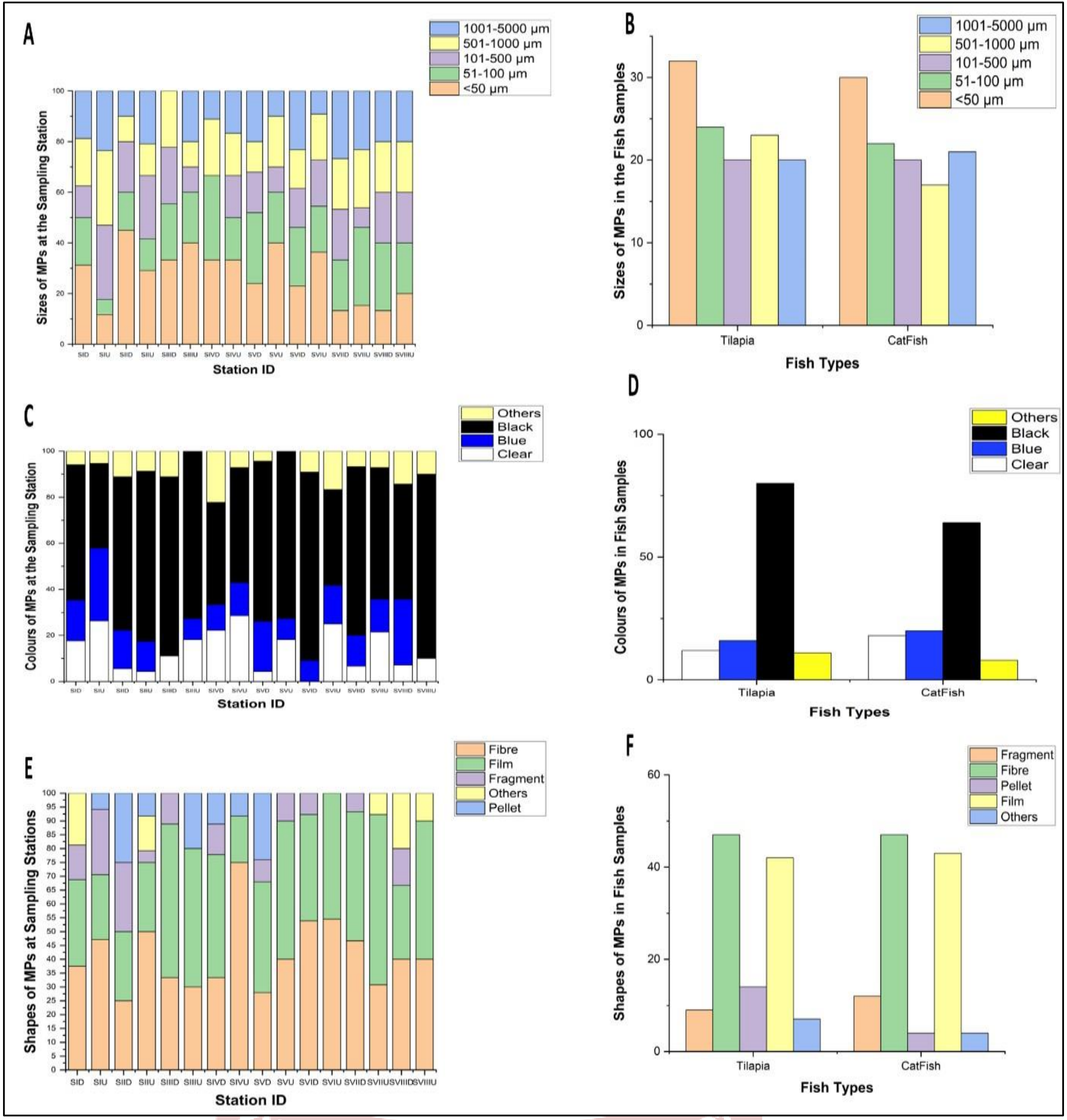


Figure 6.4: MPs Characteristics at the Sampling Stations (A – sizes, C – colours and D – shapes) and per fish types (B – sizes, D- colours and F – shapes)

6.3.3. Polymer Composition

Out of the 229 microplastics identified visually, 100 (50 from each fish type) were further analysed using infrared spectroscopy, with approximately 91% (n = 91) confirmed as synthetic polymers. The polymers identified included polyethylene (PE), polyester (PES), polystyrene (PS), polyamide (PA), and polypropylene (PP) (Figure 6.5). Among these, PE was the most common (29.7%), followed by PP (25.3%), PES (18.7%), PA (14.3%), and PS (12.1%). Each polymer showed distinct infrared spectral features: PE at around 2900 cm^{-1}, PA at 3450 cm^{-1}, PS at 1530 cm^{-1}, and PP with peaks near 765 cm^{-1} and 3000 cm^{-1} (Figure 4). These spectral signatures helped confirm the identity of the microplastic types.

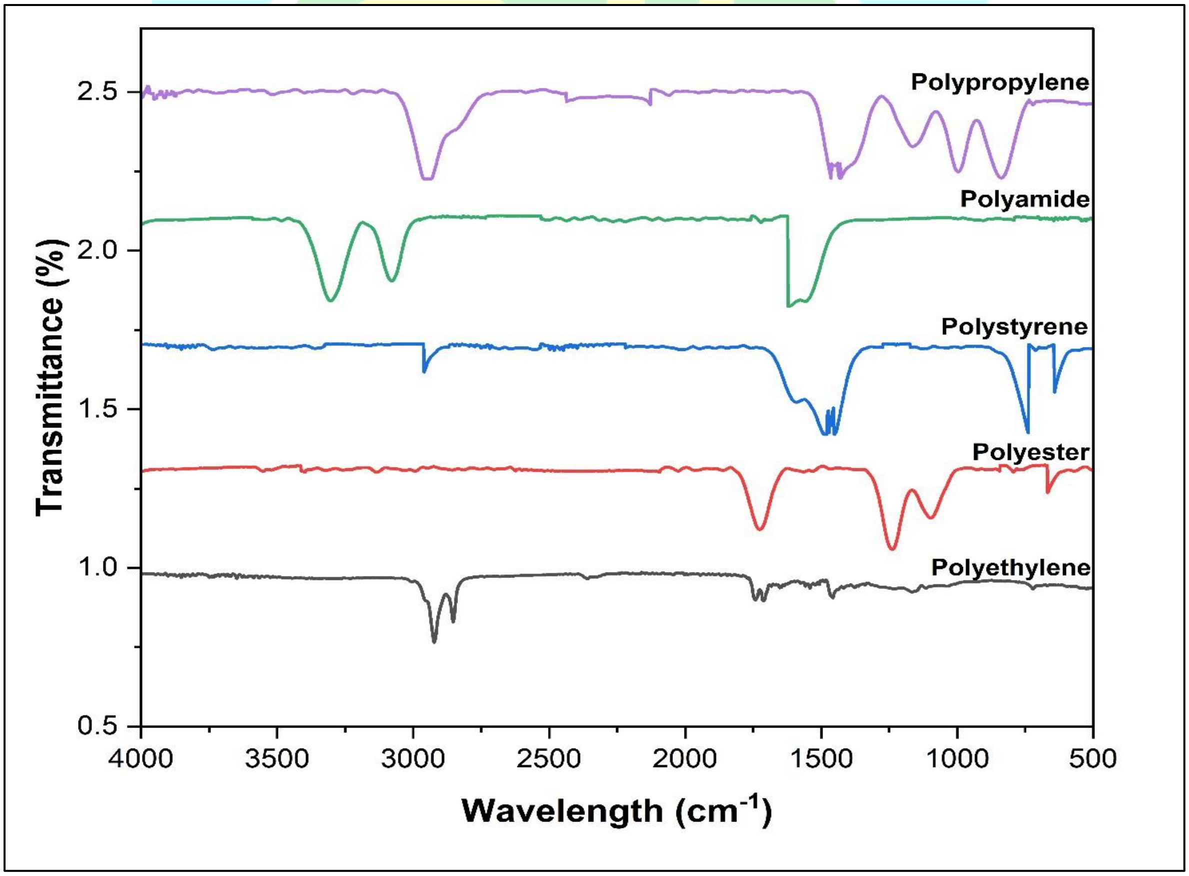


Figure 6.5: FTIR spectra of identified polymers in fish from Lake Volta

6.3.4. Relational Analysis

A Spearman correlation analysis conducted across all sampled fish revealed a strong positive correlation between total length and body weight ($r = 0.83$, $p < 0.0001$), suggesting that larger individuals possess proportionally greater mass (Table 6.3). Conversely, a moderate negative correlation was observed between total length and condition factor ($r = –0.42$, $p < 0.0001$), indicating that longer fish may exhibit reduced relative body condition. In contrast, no statistically significant relationships were found between microplastic (MP) abundance and any morphometric parameter. Specifically, correlations between MP load and total length ($r = –0.15$, $p = 0.135$), body weight ($r = –0.11$, $p = 0.279$), and condition factor ($r = 0.10$, $p = 0.341$) were all weak and non-significant. These findings suggest that MP ingestion is not associated with fish size or condition in the present study. The results indicate no significant relationship between fish size and MP ingestion. Similarly, the analysis supports the null hypothesis of no significant correlation between the condition factor and MP ingestion.

Table 6.3: Relationship between MPs abundance and morphometric characteristics of fish samples from Lake Volta

		Total Length	**Body Weight**	**Condition Factor**	**MPs**
Total Length	Spearman Corr.	1			
	p-value				
Body Weight	Spearman Corr.	0.83206	1		

	p-value	<0.0001			
Condition Factor	Spearman Corr.	--0.41872	0.08542	1	
	p-value	<0.0001	0.40797		
MPs	Spearman Corr.	-0.15257	-0.11171	0.09824	1
	p-value	0.13522	0.27856	0.34099	

2-tailed test of significance is used

Fish belonging to Tilapia showed high positive association between total length and body weight (r = 0.951, p < 0.0001), which aligns with general growth tendencies (Table 6.4). Furthermore, a weak but statistically significant positive connection was discovered between body weight and condition factor (r = 0.401, p = 0.0047), showing that bigger fish may be in somewhat better condition. There were no significant connections between MPs and total length of Tilapia (r = -0.250, p = 0.086), body weight (r = -0.212, p = 0.0.147), or condition factor (r = -0.090, p = 0.542). These results support the null hypothesis that MP ingestion is not significantly influenced by fish size or health condition in Tilapia.

Table 6.4: Relationship between MPs abundance and morphometric characteristics of Tilapia species sampled from Lake Volta

	Total Length (tilapia)	**Body Weight**	**MPs**	**Condition Factor**

Total Length (tilapia)	Spearman Corr.	1			
	p-value				
Body Weight	Spearman Corr.	0.95135	1		
	p-value	<0.0001			
MPs	Spearman Corr.	-0.25031	0.21244	1	
	p-value	0.08618	0.14716		
Condition Factor	Spearman Corr.	0.17727	0.40111	-0.09023	1
	p-value	0.22806	0.00472	0.54194	

2-tailed test of significance is used

Similarly, in catfish, total length and body weight were highly positively correlated (r = 0.951, p < 0.0001), while total length had moderate correlations with condition factor (r = -0.485, 0.0005), indicating that larger fish may be in relatively poorer condition (Table 6.5). Catfish, like Tilapia, showed no significant associations between MPs and any morphometric parameter, confirming the apparent independence of MP accumulation from size or condition measures. These findings support the null hypothesis for both MP-size and MP-condition factor relationships.

Table 6.5: Relationship between MPs abundance and Morphometric Characteristics of Catfish Species from Lake Volta

		Total Length (Catfish)	**Body Weight**	**MPs**	**Condition Factor**
Total Length (Catfish)	Spearman Corr. p-value	1			
Body Weight	Spearman Corr.	0.95108	1		
	p-value	<0.0001			
MPs	Spearman Corr.	-0.00519	0.01936	1	
	p-value	0.97205	0.89609	--	
Condition Factor	Spearman Corr.	-0.48469	-0.22766	0.0061	1
	p-value	4.81063E-4	0.11966	0.9672	--

2-tailed test of significance is used

6.3.5. Bioaccumulation

MP concentrations in fish tissues varied considerably across sites and species. Tilapia generally accumulated higher MPs than catfish, with the highest concentrations observed at SVD (221.74 MPs/kg) and SIIU (123.00 MPs/kg). Catfish also showed elevated levels at SIVU (189.20 MPs/kg) and SVIIU (115.46 MPs/kg). Bioaccumulation factors (BAFs) were consistently higher for tilapia, peaking at SIIU (30.75 L/kg) and SIIIU (15.61 L/kg), indicating stronger uptake from water. Biota–sediment accumulation factors (BSAFs) were comparatively low across all sites, with values rarely exceeding 1.0, except localised elevations in SID and SVIIU catfish (4.43 and 4.33, respectively). Across all sites, water was the dominant exposure route. (Table 6.6)

Table 6.6: Bioaccumulation by sites and fish types from Lake Volta

Site	Fish Type	Number of Fish	Mean C_{fish} (MPs/kg)	Mean MPs in Water (MPs/L)	MPs in Sediment (MPs/kg)	BAF (L/kg)	BSAF	Dominant Route
SID	Tilapia	3	83.33	14.67	26.67	5.68	3.13	Water
SID	Catfish	3	118.01	14.67	26.67	8.05	4.43	Water
SIU	Tilapia	3	16.95	16.67	240.00	1.02	0.07	Water
SIU	Catfish	3	48.90	16.67	240.00	2.93	0.20	Water

SIID	Tilapia	3	41.71	16.67	106.67	2.50	0.39	Water
SIID	Catfish	3	27.01	16.67	106.67	1.62	0.25	Water
SIIU	Tilapia	3	123.00	4.00	426.67	30.75	0.29	Water
SIIU	Catfish	3	39.02	4.00	426.67	9.75	0.09	Water
SIIID	Tilapia	3	12.63	13.33	100.00	0.95	0.13	Water
SIIID	Catfish	3	15.79	13.33	100.00	1.18	0.16	Water
SIIIU	Tilapia	3	41.63	2.67	40.00	15.61	1.04	Water
SIIIU	Catfish	3	10.01	2.67	40.00	3.75	0.25	Water

SIVD	Tilapia	3	47.09	13.33	120.00	3.53	0.39	Water
SIVD	Catfish	3	80.94	13.33	120.00	6.07	0.67	Water
SIVU	Tilapia	3	35.83	12.67	86.67	2.83	0.41	Water
SIVU	Catfish	3	189.20	12.67	86.67	14.94	2.18	Water
SVD	Tilapia	3	221.74	10.00	240.00	22.17	0.92	Water
SVD	Catfish	3	191.76	10.00	240.00	19.18	0.80	Water
SVU	Tilapia	3	27.36	6.67	26.67	4.10	1.03	Water
SVU	Catfish	3	9.39	6.67	26.67	1.41	0.35	Water

SVID	Tilapia	3	8.45	46.67	320.00	0.18	0.03	Water
SVID	Catfish	3	32.31	46.67	320.00	0.69	0.10	Water
SVIU	Tilapia	3	35.35	24.00	93.33	1.47	0.38	Water
SVIU	Catfish	3	56.03	24.00	93.33	2.33	0.60	Water
SVIID	Tilapia	3	57.12	28.67	286.67	1.99	0.20	Water
SVIID	Catfish	3	113.76	28.67	286.67	3.97	0.40	Water
SVIIU	Tilapia	3	77.34	16.67	26.67	4.64	2.90	Water
SVIIU	Catfish	3	115.46	16.67	26.67	6.93	4.33	Water

SVIIID	Tilapia	3	80.40	9.33	86.67	8.61	0.93	Water
SVIIID	Catfish	3	129.40	9.33	86.67	13.86	1.49	Water
SVIIIU	Tilapia	3	71.71	18.00	146.67	3.98	0.49	Water
SVIIIU	Catfish	3	17.81	18.00	146.67	0.99	0.12	Water

6.4. Discussions

This study assessed microplastic (MP) ingestion in freshwater fish, specifically tilapia and catfish, from Lake Volta. Consistent with findings by (Awewomom et al., 2024), the results revealed marked spatial variability in MP abundance across the 16 sampling stations, attributed primarily to a combination of anthropogenic inputs and environmental dynamics. The highest MP abundance was recorded at Dambai (Station SVD), with catfish exhibiting peak values of up to 16 particles per individual, whereas locations such as Makango, Kafaba No. 2, and Accrape exhibited minimal contamination (Figure 6.3).

MPs ingestion also varied significantly across species and habitat types (Table 6.2). For instance, tilapia species such as *C. zilli*, a benthic herbivore, had the highest MP burden among all species sampled (2.59 ± 1.3 items per fish), reinforcing the role of sedimentassociated feeding behaviors in increasing MP exposure. Similarly, *C. nigrodigitatus*, a benthic catfish, exhibited substantial ingestion levels (2.56 ± 2.0 MPs per fish). These patterns support earlier evidence that benthic habitats act as MP sinks due to sedimentation processes (Wright et al., 2013; Boateng et al., 2024). Interestingly, across most stations, tilapia species demonstrated higher MP loads than catfish, a trend potentially linked to species-specific foraging strategies, as well as spatial variability in pollution sources such as urban runoff and hydrodynamic factors like dilution and deposition (Figure 6.3). Collectively, these findings underscore the importance of site-specific monitoring and mitigation efforts, particularly in high-risk zones like Dambai, to reduce plastic inputs into freshwater ecosystems.

The maximum microplastic (MP) abundance observed in this study, up to 16 items per individual fish, is consistent with the upper thresholds reported in previous assessments of Lake Volta, such as the 17 items per fish documented by (Boateng et al., 2024). However, the average MP count per individual, calculated at 2.39 ± 1.52 particles (2.47 ± 1.30 items/individual for tilapia and 2.29 ± 1.73 items/individual), is considerably lower than the average values reported for fish in the lower part of the lake, where more intense anthropogenic activities such as industrial discharge and urban waste influx are prevalent (Boateng et al., 2024; Bruce-Vanderpuije et al., 2025). This discrepancy highlights the spatial heterogeneity of MP pollution within Lake Volta, likely influenced by differential land use patterns, population densities, and localised waste management practices.

Despite being lower than some localised hotspots within the same lake system, the average value recorded in this study aligns well with observations in comparable freshwater ecosystems, where MP ingestion typically ranges from 1 to 3 items per fish (Adu-Boahen et al., 2020; Akindele et al., 2019; Blankson et al., 2022; Piyawardhana et al., 2022). Such findings reinforce the notion that while the contamination of MPs is ubiquitous and persistent in aquatic biota, it is also highly variable, depending on both environmental exposure and species-specific feeding behaviours. These results underscore the importance of continued monitoring and spatially resolved assessments to capture the complexity of microplastic distribution in freshwater ecosystems like Lake Volta.

Interspecific differences were evident in the biometric characteristics of the sampled fish. Catfish exhibited greater average total lengths (19.3 ± 6.52 cm) compared to tilapia (14.1 ± 3.80 cm); however, tilapia demonstrated significantly higher condition factors ($K = 2.11 \pm 0.36$) than catfish ($K = 0.79 \pm 0.18$), suggesting that tilapia were in better physiological condition overall. These observations are consistent with findings reported by (Okwodu et al., 2022), who also noted higher condition indices in tilapia species relative to catfish species in a freshwater like Lake Volta, reflecting their superior adaptability and somatic robustness in varied aquatic environments. Despite MP ingestion, this higher K value in tilapia could suggest greater environmental adaptability or energy utilisation efficiency (Tibihika et al., 2018). Notably, a strong positive correlation was observed between fish abundance and MP abundance ($r = 0.99$, $p < 0.0001$), indicating that population density may play a role in exposure or ingestion rates.

The bulk of the particles consumed by tilapia and catfish were microplastics smaller than 50 µm, with tilapia consuming the greatest percentage of these tiny pieces (Figure 6.4 A–B). Such dominance of sub-50 µm MPs raises significant concerns about the bioavailability and potential for trophic transfer of these particles in freshwater food webs. Consistent with observations by Nchimbi et al. (2024) and Bruce-Vanderpuije et al. (2025), our colourimetric analysis identified black MPs as the most prevalent, followed by blue particles (Figure 6.4 C–D), likely reflecting the regional prevalence of discarded fishing gear and household packaging materials. Morphological characterisation further revealed that microfibres and films were the predominant shapes recovered across sampling sites; notably, catfish ingest more fragmented particles, whereas tilapia exhibited a higher incidence of spherical pellets (Figure 6.4 E–F). These patterns align with feeding-mode hypotheses advanced by Nchimbi et al. (2024), Boateng et al. (2024), and Amponsah et al. (2024) suggesting that differences in species-specific foraging strategies and habitat use dictate MP exposure pathways. Moreover, Fourier-transform infrared (FTIR) spectroscopy of a subset of 100 particles confirmed that 91 % were anthropogenic polymers—primarily polyethylene (PE), polypropylene (PP), and polyester (PES)—echoing the polymer distributions reported by (Egessa et al., 2020; Hamed et al., 2023) and (Piyawardhana et al., 2022). The characteristic spectral peaks (e.g., 2,900 cm^{-1} for PE, 3,000 cm^{-1} for PP) validated these identifications, underscoring the linkage between local plastic consumption patterns and the composition of environmental MPs (Figure 6.5).

A statistically significant positive correlation ($r = 0.83$, $p < 0.0001$) was found between total length and body weight across all species studied (Table 6.3). This suggests that fish's mass grows proportionately as their length increases, which is consistent with normal growth dynamics (Nchimbi et al., 2024). On the other hand, overall length and condition factor have a moderately significant negative correlation ($r = -0.42$, $p < 0.0001$), which implies that larger fish might be in comparatively worse physiological condition. This could be due to ecological pressures, such as limited food availability or energy trade-offs related to somatic growth. Interestingly, no significant relationship was found between the abundance of MPs and any of the observed morphometric characteristics, such as condition factor (r = 0.10, p = 0.341), body weight (r = -0.11, p = 0.279), or total length (r = -0.15, p = 0.135). Species-specific analyses of catfish (Table 6.5) and tilapia (Table 6.4) further confirmed this lack of relationship, with similarly non-significant correlations observed across all variables. These findings suggest that exposure is more likely to be influenced by behavioural and environmental factors, such as habitat utilisation and feeding techniques, rather than by morphometric traits, as MP ingestion occurred in this study regardless of fish size or physiological condition.

This finding is consistent with previous research by (de Vries et al., 2020) and (Vendel et al., 2017), who found that MP ingestion occurs regardless of fish size or physiological condition. These investigations, including the current one, show that MP contamination is widespread and does not impact fish based on morphometric or health-related criteria. Microplastic contamination appears to be a pervasive and indiscriminate stressor in aquatic environments, affecting fish of various sizes, trophic levels, and physiological states. Furthermore, the current study supports previous research by showing that MPs were consumed by species from multiple feeding guilds, including omnivores, herbivores, and carnivores, and that differences in anthropogenic pressures across sampling sites had no significant effect on MP ingestion rates. This highlights the complexities of MP exposure routes, implying that background environmental contamination and species-specific behaviours may be more important in determining MP intake than localised human activity alone.

Patterns in MP accumulation reflect species-specific feeding habits and environmental conditions. Tilapia, as filter and surface feeders, exhibited enhanced uptake from water, consistent with higher BAFs, while catfish, being benthic feeders, showed lower tissue concentrations despite elevated sediment MP levels (e.g., SIU, SIIU, SVID), suggesting reduced sediment bioavailability or limited trophic transfer. Elevated MPs in SVD tilapia and catfish indicate localised hotspots where both water and sediment may contribute, though water-mediated transfer dominates. This aligns with regional studies in Lake Volta, where fish contamination correlated more strongly with waterborne MPs than with sediments, despite sediments containing far higher loads (Boateng et al., 2024; BruceVanderpuije et al., 2025). Similarly, a global review of 144 studies confirmed that although sediments generally hold greater MP concentrations, bioaccumulation in freshwater fish is primarily linked to water column levels through ingestion and gill uptake (Augustus de Araújo et al., 2025; Cera & Scalici, 2021). Collectively, these findings reinforce that waterborne MPs, not sediments, are the dominant exposure route across species, systems, and regions.

Recent studies in Lake Volta support the findings of this paper. They highlight that waterborne microplastics (MPs) contribute to contamination in fish, not sediment. For example, a study in the Volta Basin reported an average of 71 to 365 MPs per fish, while sediment levels were about 1,950 MPs per kilogram and water contained 111 MPs per litre (Bruce-Vanderpuije et al., 2025). However, fish contamination was more closely related to water levels. This validates that BAF often exceeds the BSAF, despite the higher sediment loads. Another survey in Lake Volta found that Nile tilapia averaged approximately 2.8 MPs per fish, with microfibers matching sediment profiles. This again showed no evidence that sediment is the main exposure route (Boateng et al., 2024). Together, these regional findings strengthen the data. Even benthic and cage-reared species accumulate MPs primarily through water. A 2025 global review of 144 studies across 45 countries found widespread MP ingestion in wild freshwater fish. This included many omnivores, around 80%, often found in stomach and gill tissues (De Araújo et al., 2025). Another systematic overview revealed similar patterns. Although sediments typically have higher MP levels, fish bioaccumulation is more strongly connected to water column concentrations. This is likely due to ingestion and gill uptake (Cera & Scalici, 2021). Waterborne MPs are the main cause of fish contamination in freshwater ecosystems worldwide, regardless of species niche or sediment load.

The widespread detection of MPs in commercially important fish species raises significant ecological and public health concerns. While current condition factors suggest no immediate physiological harm, chronic MP exposure could lead to long-term sublethal effects like inflammation, hormonal disruption, or behavioural changes. Since tilapia and catfish form a substantial part of the local diet, the potential for human exposure through consumption is considerable. This study provides vital baseline data for Lake Volta, highlighting the urgency for pollution control, long-term ecological monitoring, and public health interventions to mitigate microplastic risks in freshwater ecosystems.

6.5. Conclusion

This study measured MP abundance and features in two economically important freshwater fish, tilapia and catfish, and investigated the link between MP load and fish morphology. The MP burden varied greatly between the 16 sampling stations, with Dambai having the highest average abundance. General average MPs per fish were 2.39 ± 1.52, with averages of 2.47 ± 1.30 items/individual and 2.29 ± 1.73 items/individual for tilapia and catfish respectively. Normalised to wet body weight, concentrations were 0.07 ± 0.08 MPs/g for tilapia and 0.06 ± 0.07 MPs/g for catfish. A Mann-Whitney test revealed no significant difference in MP consumption between the tilapia and catfish sampled ($U = 412$, $p = 0.44$, rank-biserial correlation $r = 0.08$). Morphometric indexes (e.g., body wet weight, total length, and condition factor) did not predict MP load; instead, species-specific feeding methods and trophic environment are likely to regulate ingestion rates. Microplastics less than 50 µm, microfibres, and black-coloured MPs were found to be the most prevalent in terms of sizes, shapes, and colours. Polymer identification also revealed polyethylene and polypropylene as the major polymers, indicating widespread home and artisanal fishing activity. Microplastic bioaccumulation in fish is primarily water-driven, with tilapia exhibiting stronger uptake than catfish. Sediment contributions appear minimal, despite elevated loads, highlighting differential bioavailability between compartments. Sitespecific hotspots (SVD, SIIU, SIVU) indicate localised risks where MPs in water drive significant fish contamination. These findings emphasise the importance of waterborne MPs as the dominant exposure route and suggest species ecology plays a key role in bioaccumulation dynamics. A key limitation of this study is the absence of field and laboratory blanks. This omission prevents us from quantifying or correcting for background contamination, particularly airborne fibres, which may lead to overestimation of microplastic abundance. While contamination-minimisation measures were taken (e.g., use of glassware, covered containers, cotton lab coats), future studies should include procedural and field blanks to ensure more robust quality assurance. Also, a funding-driven geographic constraints and a dependence on a limited ATR-FTIR spectral library hampered polymer identification for a subset of particles. Future research should increase sample numbers per stratum, and use a more extensive spectral database to refine polymer assignments and better understand the causes of MP uptake in freshwater biota.

6.6. Bridging to Chapter 7: Integrating Multi-Matrix Findings

The detection of microplastics in fish tissues completes the exposure pathway from human activity to environmental contamination to biological uptake. To develop a comprehensive understanding of pollution dynamics in Lake Volta, these biological findings must be integrated with environmental data. Chapter 7 therefore synthesises information from all sampled matrices—water, sediment, and biota—and examines their relationships with key physicochemical parameters. This integrated analysis provides a holistic view of microplastic pollution in Lake Volta, connecting findings across compartments to inform targeted management strategies.

CHAPTER SEVEN

Multi-matrix assessment of microplastics and physicochemical dynamics in Lake Volta

Abstract

Spatio-environmental controls on microplastics (MPs) and core physicochemical parameters in Lake Volta, Ghana, were assessed using in-situ measurements and multivariate/spatial modelling. Temperatures were consistently warm (28.9–32.4 °C), pH largely suitable for aquatic life (6.76–9.00) with 13 readings > 8.5, electrical conductivity (EC) and total dissolved solids (TDS) indicated low ionic strength (EC 54.1–92.7 µS cm^{-1}; TDS 26.2–46.4 mg L^{-1}), and dissolved oxygen (DO) was generally adequate (4.7–12.9 mg L^{-1}), though Atimpoku (2D) showed localised depletion (4.7–4.9 mg L^{-1}). EC and TDS were tightly coupled ($r = 0.874$, $p < 0.001$). Variogram analysis indicated exponential models best fit temperature, pH, and TDS, whereas spherical/Gaussian structures better captured EC, DO, and salinity, with higher prediction errors for EC and DO reflecting local drivers. MPs in tilapia were negatively associated with pH and DO, and strongly correlated with MPs in catfish, indicating shared exposure pathways. Principal component analysis loaded EC, TDS, salinity on PC1, and clustering resolved site regimes dominated by (i) sediment MPs/low salinity, (ii) surface-water MPs, and (iii) fish MPs aligned with higher EC/TDS. Collectively, Lake Volta remains a low-salinity tropical freshwater system with localised physicochemical anomalies that coincide with MPs patterns, underscoring the need for integrated, spatially explicit monitoring and targeted mitigation at high-risk reaches.

7.1. Introduction

Water pollution is a serious threat to biodiversity, aquatic ecosystems, and human health (Andoh et al., 2025b). Plastic waste is one of the most widespread pollutants in waterbodies worldwide, especially freshwater systems (Isukuru et al., 2024; Shekoohiyan & Akbarzadeh, 2022). This issue worsens due to pollution from urban waste, agricultural runoff, and industrial discharge, which leads to significant ecological and economic consequences (du Plessis, 2022; Hussein, 2018; Mishra et al., 2023). Among these pollutants, microplastics (MPs) stand out because they are common, long-lasting, and can harm aquatic organisms and ecosystem processes (Egessa et al., 2020; Piskuła & Astel, 2023).

MPs are defined as plastic particles smaller than 5 mm. They come from both primary sources, such as microbeads in personal care products, and secondary sources, like the breakdown of larger plastic items (Andoh et al., 2024; Biginagwa et al., 2016; Mutuku et al., 2024). Their small size allows them to move easily within the environment and be ingested by aquatic animals. In freshwater systems, they can affect important water quality factors like pH, turbidity, dissolved oxygen (DO), and nutrient levels, which can disrupt food webs and threaten ecosystem balance (Matavos-Aramyan, 2024; Pal et al., 2025; Swain et al., 2025).

The relationship between MPs and water quality parameters (WQPs) have been studied globally. For example, changes in pH and salinity is said to affect their surface properties, thereby impacting their ability to absorb heavy metals and organic pollutants (Wang et al., 2021). Temperature, as shown by Rostampour et al. (2025) speeds up the breakdown of plastic, leading to higher MP concentrations in warmer waters. Eamrat et al. (2022) found higher MP levels in rivers with high biological oxygen demand (BOD_5), low dissolved oxygen (DO), and high total nitrogen (T-N) and total phosphorus (T-P). Wang et al. (2024) demonstrated that MPs concentration in Lake Wuliangsuhai was positively correlated with salinity, suggesting that specific physicochemical parameters can drive MPs distribution. Anuar et al. (2023) showed a strong positive link between turbidity and MP presence, indicating that suspended solids help transport and spread MPs.

Despite these findings, research on the relationship between MPs and WQPs in sub-Saharan Africa is still limited. Biginagwa et al. (2016), found a strong connection between turbidity and MPs in Lake Victoria, suggesting that they often travel with sediments and organic matter. Pal et al. (2024) reported that low pH levels in water bodies speed up plastic breakdown, increasing their presence in the water.

In Ghana, research on MPs is still developing and hence lacks the relevant literature on this MPs and water quality parameters relationship. However, some earlier studies could be put into perspective to make a case for the relationship. For instance, Karikari et al. (2009) reported extremely low DO, high biochemical oxygen demand, and elevated suspended solids at the Korle Lagoon estuary, indicating severe organic pollution. Deheyn et al. (2024) later found exceptionally high levels of MPs and microfibers near the Kantamanto market and Korle Lagoon, far exceeding global coastal baselines. These findings collectively highlight a direct link between degraded water quality and elevated MPs contamination in Accra's aquatic systems. Gonçalves et al. (2025) linked coastal plastic pollution to inadequate waste management systems. However, the linkage between MPs abundance and these WQPs in freshwater ecosystems like Lake Volta, a crucial body of water for fisheries, transport, and hydropower, have limited studies.

Combining MPs data from different environmental areas, such as sediment, surface water, and fish, with water quality factors is vital for a complete understanding of pollution sources, pathways, and potential impacts. This study fills that gap by comparing findings from two earlier studies on Lake Volta: one looked at MPs in sediment and water, while the other focused on MPs in fish (tilapia and catfish) (Andoh et al., 2025b). Merging these datasets alongside the WQPs provides a unique chance to explore the relationships between water quality and MP pollution in a tropical freshwater ecosystem like Lake Volta.

In light of the above, this study aims to (1) assess WQPs across 16 sampling sites, (2) explore the link between MPs amounts and water quality indicators, and (3) explore patterns and groupings among sampling sites based on MPs load and WQPs to help manage Lake Volta and the other freshwater resources in Ghana.

7.2. Materials and Methods

7.2.1. Study Area

Lake Volta, located in Ghana, is the country's largest freshwater reservoir and one of the largest artificial lakes in the world by surface area. It spans approximately 8,502 km², covering about 3.6% of Ghana's total land area (Tsikata, 2006; Barry et al., 2007). Formed in the 1960s following the construction of the Akosombo Dam primarily for hydroelectric power generation, the lake has since evolved into a multifunctional resource.

Today, Lake Volta supports a wide array of socio-economic activities, including inland fishing, irrigation-based agriculture, transportation, and aquaculture. It also serves as a vital source of drinking water for several riparian communities and plays a central role in local livelihoods and food security (Elegbede, et. al., 2015; FAO, 2016). Despite its benefits, the lake faces increasing anthropogenic pressures (Kakari et al., 2013). The communities that rely heavily on the lake for their daily water and economic needs are, paradoxically, also those whose activities, such as overfishing, unsustainable farming, and waste discharge, pose threats to its ecological balance. These interactions underline the importance of closely monitoring the water quality and usage patterns around Lake Volta.

For this study, sixteen communities situated along the lake were selected as sampling sites, chosen based on both their geographical distribution and accessibility (Figure 7.1). These sites are grouped into upstream (U) and downstream (D) segments across eight strata, following the spatial classification system adopted by the Food and Agriculture Organization (FAO) for fishery data collection (Kakari et al., 2013). The communities are as follows:

Stratum 1: 1D – Akateng, 1U – Kotoso
Stratum 2: 2D – Atimpoku, 2U – Dzemeni
Stratum 3: 3D – Kpebe, 3U – Dafor Tornu
Stratum 4: 4D – Odormitor, 4U – Ayarifie Bator/Tokuroano Bator
Stratum 5: 5D – Dambai, 5U – Kitari
Stratum 6: 6D – Kete-Krachi, 6U – Grubi
Stratum 7: 7D – Lonto, 7U – Makango
Stratum 8: 8D – Kafaba No. 2, 8U – Accrape

These communities, illustrated in Figure 7.1, provide a representative cross-section of human-environment interactions along the lake and form the basis for understanding spatial variation in water quality and use.

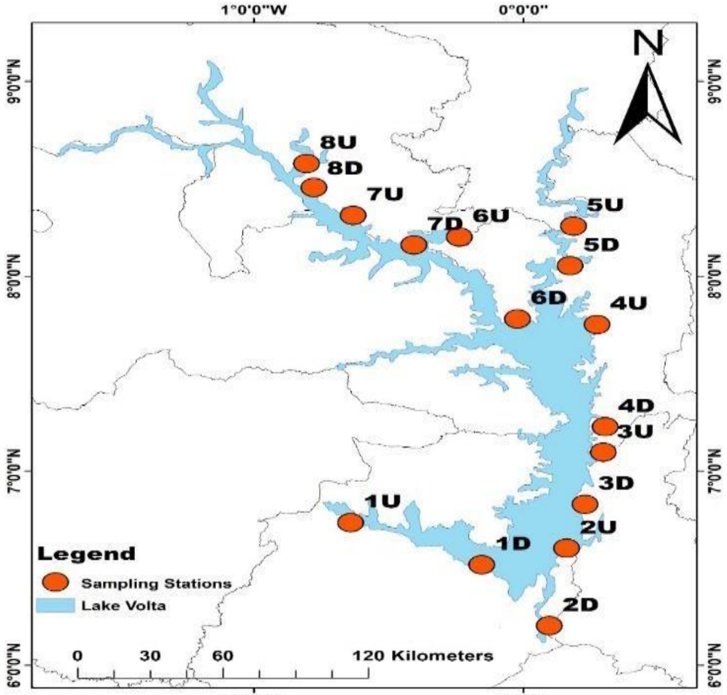


Figure 7.1: Sampling stations along Lake Volta. Strata are numbered 1–8, with D denoting downstream and U upstream, adapted from Andoh et al. (2025b).

7.2.2. Data Sources and Framework

This study combines MP concentration data from surface water, sediment, and fish samples, along with water quality measurements, from 16 mapped sampling stations in Lake Volta. The MP data were obtained from two earlier studies conducted in the same area, presented in Chapters Five and Six.

Surface water and sediment samples were collected, prepared, and tested for MPs as part of an earlier study by Andoh et al. (2025b). Fish samples, which show the accumulation of MPs in living organisms, were collected and processed in another study by in Chapter 6. Both studies followed standard methods for collecting samples, digesting them, and identifying MPs.

For this analysis, average MP concentrations from each environmental compartment (water, sediment, and fish) were gathered and standardised across the 16 sampling stations. These stations match locations where WQPs such as temperature, pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and dissolved oxygen (DO), were measured at the same time. This combined dataset allows for a detailed assessment of the links between MP contamination and water quality in Lake Volta.

7.2.3. Water Quality Sample Collection

At each sampling station, in situ measurements of physicochemical parameters were taken every morning, including temperature (°C), pH, dissolved oxygen (DO; mg/L), electrical conductivity (EC; µS/cm), salinity (ppt), and total dissolved solids (TDS; mg/L). Measurements were performed using the AZ digital Water Quality Tester (COMBO meter probe, version 86031; WIZSensor Technology Co. Ltd., China), deployed concurrently with the collection of water, sediment, and fish samples in January 2024, following the field protocols of Karikari et al. (2013). Prior to deployment, all sensors were calibrated against traceable standards, with on-site recalibration checks conducted to ensure measurement integrity. Specifically, pH was calibrated with fresh buffer solutions (pH 4.0, 7.0, and 10.0), conductivity/TDS with a KCl standard solution bracketing the expected range, and DO with air-saturated water, while salinity was verified through conductivity calibration.

During measurements, the probe was immersed to a depth of 2 cm and held steady for 1–2 minutes to allow stabilisation before readings were logged. To capture within-site variability and enhance representativeness, each parameter was measured three times at different points at 5 - 10 m apart arranged in a triangle (exceeding the GPS error yet within the same water mass) within the sampling location. Sampling coordinates were georeferenced using a Garmin GPSMAP 67i handheld GPS unit (accuracy ±3.65 m; Garmin Ltd., Taiwan) to support subsequent spatial modelling (Ghansah et al., 2022). To prevent cross-site contamination, the probe was rinsed thoroughly with distilled water between stations, and all sensors were stored and transported in accordance with manufacturer specifications, including the use of appropriate electrode storage solutions.

7.2.4. Data Analysis

OriginPro 2025 was used for all statistical analyses. MP concentrations and WQPs were compiled using descriptive statistics like mean and standard deviation for various sample types (surface water, sediment, tilapia, and catfish) and sampling locations. P-values below 0.05 are regarded as statistically significant, and all statistical tests were performed at a 5% significance level ($\alpha = 0.05$) (Zar, 2014). The dataset was carefully preprocessed before inferential analyses. In addition to environmental factors like temperature, pH, conductivity, TDS, DO, and salinity, this also included the concentrations of MPs in each matrix.

Spatial distributions of WQPs were visualised using Simple Kriging interpolation, a geostatistical method that assumes a known global mean (m) and estimates values at unsampled locations (x_0) as weighted linear combinations of observed deviations (Pirani & Modarres, 2020; Cressie, 1993; Goovaerts, 1997):

$$Z^*(x_0) = m + \sum_{i=1}^{n} \lambda_i (Z(x_i) - m) \tag{7.1}$$

Where $Z^*(x_0)$ is the predicted value at location x_0, $Z(x_i)$ are the observed values, and λ_i are kriging weights.

The weights are obtained by solving the kriging system of equations:

$$\sum_{i=1}^{n} \lambda_i C(x_i - x_j) = C\,(x_i - x_0), \quad i = 1, 2, \dots, n \tag{7.2}$$

where $C(h)$is the covariance function at lag h. The associated kriging variance, which quantifies estimation uncertainty, is expressed as:

$$\sigma_K^2\,(x_0) = C(0) = \sum_{i=1}^{n} \lambda_i C(x_i - x_0) \tag{7.3}$$

Spatial autocorrelation was characterised using semivariograms, computed as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{7.4}$$

where $N(h)$ is the number of paired observations at separation distance h. Experimental semivariograms were fitted with theoretical models (spherical, exponential, Gaussian) to ensure positive definiteness of the covariance structure.

The Kriging interpolation is a superior geostatistical method for mapping microplastic (MP) pollution in Lake Volta due to its core principle of modeling spatial autocorrelation—a fundamental characteristic of pollutants dispersing via water currents and wind (Matheron, 1963). Unlike deterministic methods, Kriging provides statistically optimal and unbiased predictions (Goovaerts, 1997) and, crucially, quantifies prediction uncertainty through variance maps (Johnston et al., 2001). This is vital for the lake's vast and complex environment, as it transforms sparse, irregular sampling data into a continuous understanding of distribution while objectively identifying areas where data is insufficient, thereby optimizing future monitoring network design.

For MP research specifically, Kriging enables cost-effective identification of probable accumulation hotspots and transport pathways, as demonstrated in analogous freshwater studies (Robinson et al., 2021). Its flexibility through techniques like Co-Kriging allows integration with secondary covariates to improve models where primary MP data is limited. Furthermore, Indicator Kriging can assess exceedance probabilities for risk management (Goovaerts, 1997). Ultimately, Kriging offers a rigorous framework not just for interpolation, but for generating defensible, spatially-explicit evidence to inform mitigation policy in large reservoirs like Lake Volta, aligning with applications in similar systems (Wright et al., 2020).

The Shapiro–Wilk test was used to evaluate the normality of continuous variables. $\text{Log}_{10}(x + 1)$, a technique appropriate for right-skewed distributions and zero values, was used to log-transform variables that deviated from normalcy (McDonald, 2014). Some variables remained non-normal even after the transformation, so non-parametric tests such as Spearman's rank correlation were used where necessary. Subsequent multivariate analyses used transformed and standardised data, reporting any residual deviations from normalcy and interpreting the results with caution (Tabachnick & Fidell, 2013).

MP concentrations and water quality parameters were compared using Pearson and Spearman correlation analysis to look for possible linear relationships. Origin2025's integrated correlation matrix tool was used to calculate Pearson correlation coefficients (r) or Spearman's correlation coefficients (ρ) and their significance (p-values). The direction and strength of bivariate relationships across environmental matrices were revealed using a colour-coded heatmap (Hair et al., 2014). PCA (Correlation Matrix Analyses) was used to reduce dimensionality and identify the important environmental gradients affecting MP distribution (Jolliffe & Cadima, 2016). Before analysis, all variables were standardised, and variable loadings and groupings were visualised using the PCA output, which included biplots, scree plots, and eigenvalues. The PCA and other unsupervised machine learning methods such as K-means (Euclidean distance method) and hierarchical clustering are powerful in MPs research for uncovering patterns in large, unlabelled datasets (Khanam et al., 2025). They aid in automated grouping of particles by physical and chemical traits and simplify the interpretation of complex spectral data, justifying their application in this study.

7.3. Results

7.3.1. Physical and Chemical Parameters

The physicochemical parameters reflected comparatively stable conditions across the sampling locations (Table 7.1). Water temperature averaged 30.38 ± 1.02 °C, with values between 28.90 and 32.40 °C; the highest temperatures occurred at Ayerifie Bator (4U) and Lonto (7D), while the lowest was observed at Akateng (1D). pH values ranged from 6.76 to 9.00 (mean = 7.96 ± 0.67). Out of 48 in situ measurements, 13 exceeded the WHO drinking water guideline of 6.5–8.5, with the most alkaline values recorded at Kitari (5U; 9.00) and Accrape (8U; 8.93). Electrical conductivity (EC) remained low across all sites (54.10–92.70 µS/cm; mean = 69.54 ± 9.17 µS/cm), and total dissolved solids (TDS) similarly fell within a narrow range (26.20–46.40 mg/L; mean = 34.16 ± 5.06 mg/L), both well below WHO thresholds. Dissolved oxygen (DO) averaged 9.52 ± 1.68 mg/L, with a wide variation from 4.70 to 12.90 mg/L; notably, Atimpoku (2D) recorded the lowest concentrations (4.70–4.90 mg/L). Salinity was consistently low across the sites, ranging from 0.03 to 0.05 ppt (mean = 0.04 ± 0.01 ppt).

Table 7.1: Summary of physicochemical parameters measured.

Parameter	**Min**	**Max**	**Average**	**SD**	**WHO (Boamah et al., 2024)**
Temperature	28.90	32.40	30.38	1.02	-
pH	6.76	9.00	7.96	0.67	6.5 – 8.5
EC	54.10	92.70	69.54	9.17	<1200
TDS	26.20	46.40	34.16	5.06	<1000
DO	4.70	12.90	9.52	1.68	8.0 - 10.0
Salinity	0.03	0.05	0.04	0.01	-

EC – Electrical Conductivity; TDS – Total Dissolved Solids; DO-Dissolved Oxygen; WHO – World Health Organization

7.3.2. Spatial Models for MPs Concentration and Water Quality Parameters

The spatial patterns of WQPs varied considerably across sites (Figure 7.2, Table 7.2). Temperature showed no consistent trend; however, upstream locations were generally warmer than downstream, except stratum 7 where Lonto (7D) recorded higher values than Makango (7U). Notably, the maximum temperature occurred at Ayirefie Battor (4U), whereas the minimum was observed at Akateng (1D). Similarly, pH values were elevated at Accrape (8U), Grubi (6U), and Kitari (4U), while Atimpoku (2D) stood out with the lowest pH. In contrast, electrical conductivity was highest at Kotoso (1U) and Accrape (8U) but markedly lower at Kitari (5U) and Grubi. Dissolved oxygen exhibited an opposite trend, reaching its peak at Kitari (5U) but dropping to its lowest at Atimpoku (2D). Salinity levels were generally low across most sites, although slightly higher concentrations were detected at Kotoso (1D). A comparable pattern was observed for total dissolved solids, with Kotoso (1U) and Accrape (8U) again recording the highest values. Modelling analyses further emphasised these spatial variations. Exponential models best captured the variability of temperature, pH, and total dissolved solids, whereas the spherical model provided the best fit for electrical conductivity, and Gaussian models were more suitable for dissolved oxygen and salinity (Table 7.2). Among these, temperature and pH were predicted most reliably, reflecting lower errors and stronger model performance. By contrast, electrical conductivity and dissolved oxygen exhibited larger errors, indicating weaker predictive accuracy.

Table 7.2: Cross-validation of prediction uncertainties in water sample variables (n = 70)

Parameter	**Models**	**ME**	**RMSE**	**RMSS**	**ASE**
Temperature	Exponential	0.0008	0.769	0.913	0.872
pH	Exponential	-0.003	0.325	0.821	0.407
Electrical Conductivity	Spherical	-0.316	3.595	0.524	6.982
Total dissolved solids	Exponential	-0.049	2.757	0.793	4.338
Dissolved oxygen	Gaussian	0.313	4.527	2.138	4.664

Salinity	Gaussian	-0.001	0.044	0.815	0.106

Note: ME – Mean Error; RMSE – Root Mean Square Error; RMSS – Root Mean Square Standardised Error; ASE – Average Standard Error

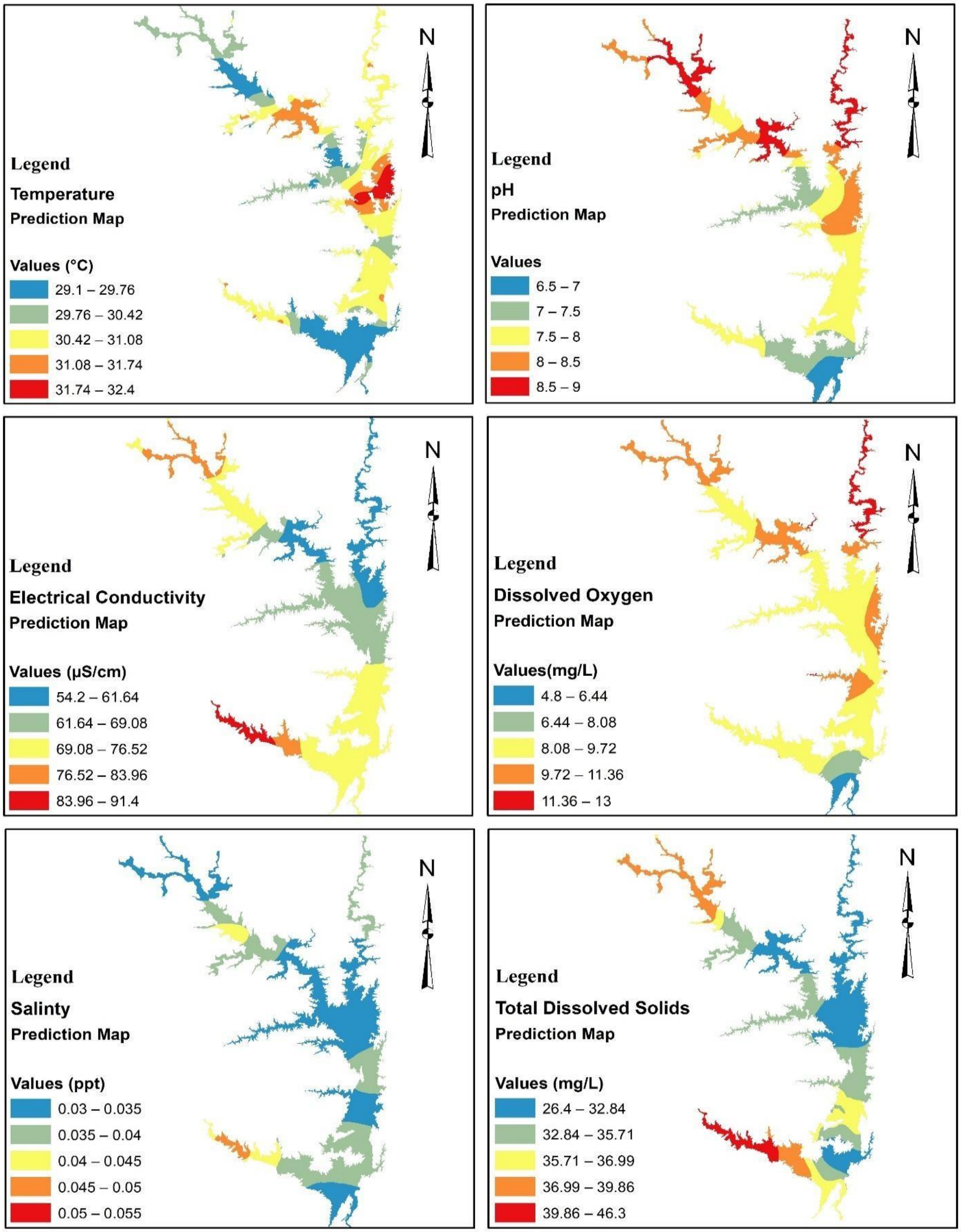


Figure 7.2: Spatial maps of WQPs across sampling stations.

7.3.3. Correlation between MPs Concentration and Water Quality Parameters

The Z-score normalised concentrations of the six important WQPs across the 16 sampling stations are displayed in this heatmap (Figure 7.3). While stations like 2D and 6D exhibit noticeable decreases, particularly in DO, pH and EC, indicating localised degradation of water quality, station 1U prominently concentrate elevated values of salinity, EC, and TDS, indicating high ionic and solute loads.

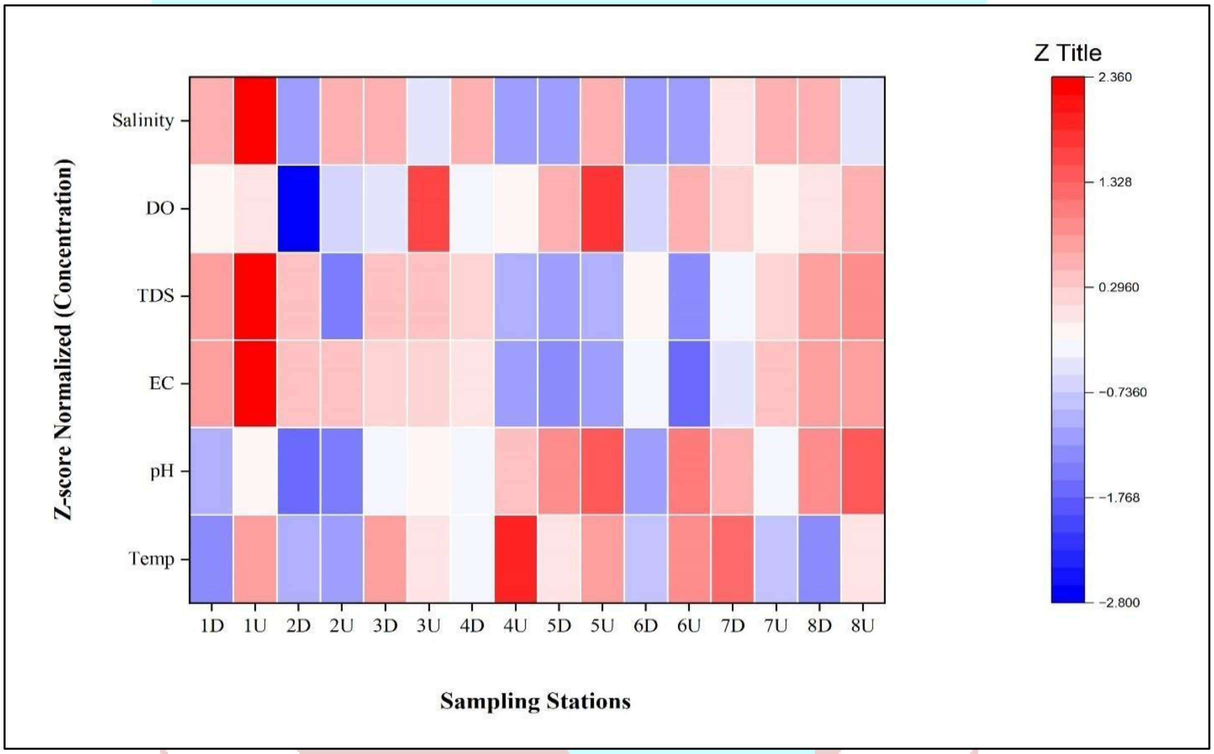


Figure 7.3: Correlation heatmap of the WQPs across the stations

As shown in Table 7.3, the relationships between MPs concentrations in different environmental matrices and WQPs were generally weak, with most correlation coefficients close to zero and non-significant. In catfish, weak to moderate negative correlations were observed across nearly all parameters, particularly with temperature (r = –0.353) and total dissolved solids (TDS; r = –0.321), while conductivity (r = –0.130), dissolved oxygen (DO; r = –0.139), salinity (r = –0.238), and pH (r = –0.170) showed weaker negative associations.

Similarly, sediment MPs exhibited mostly weak correlations, including small positive values with conductivity (r = 0.068) and temperature (r = 0.074), and weak negative values with DO (r = –0.317), salinity (r = –0.168), TDS (r = –0.111), and pH (r = –0.175).

In surface water, correlations remained close to zero, with small positive coefficients for temperature (r = 0.128) and TDS (r = 0.178), and weak negative associations with conductivity (r = –0.051), DO (r = –0.174), salinity (r = –0.266), and pH (r = –0.025). By contrast, MPs in tilapia showed stronger relationships with several parameters. A moderate positive correlation was found with conductivity (r = 0.372), while TDS (r = 0.103) and salinity (r = 0.135) exhibited weak positive values. In contrast, negative correlations were observed with temperature (r = –0.326) and DO (r = –0.480). Most notably, pH displayed a significant moderate negative correlation with MPs in tilapia (r = –0.527, $p < 0.05$), indicating that increasing pH was associated with a decline in MPs levels in this species.

Table 7.3: Correlation matrix of microplastic concentrations and WQPs.

Parameters	MPs in Catfish	MPs in Sediment	MPs in Surface Water	MPs in Tilapia
Conductivity	-0.13	0.068	-0.051	0.372
DO	-0.139	-0.317	-0.174	-0.48
Salinity	-0.238	-0.168	-0.266	0.135
TDS	-0.321	-0.111	0.178	0.103
Temperature	-0.353	0.074	0.128	-0.326
pH	-0.17	-0.175	-0.025	-0.527*

Note: * Significance level for $p < 0.05$

7.3.4. Principal Component Analysis

To investigate the fundamental structure of WQPs and the distribution of MPs in water, sediment, and biota, PCA was used. Figure 7.4A presents a three-dimensional Principal Component Analysis (PCA) biplot that shows the correlations between WQPs (e.g., EC, TDS, salinity, DO, pH, temperature) and the concentrations of MPs across environmental matrices (sediment, surface water, tilapia, and catfish). 71.36% of the variance was explained by the first three principal components (PC1 = 32.93%, PC2 = 23.83%, and PC3 = 14.60%), suggesting a significant dimensional reduction with little information loss. Temperature and surface water MPs are more closely linked to PC3, whereas electrical conductivity (EC), TDS, and salinity are strongly correlated with PC1 and PC2. There was also an MPs partitioning axis (PC2–PC3) that separated MPs retained in surface water and sediment from MPs that biologically accumulated (in tilapia and catfish). Sites grouped along these axes represent common MPs loads and physicochemical conditions; for example, sites 1U, 2D, and 8D have a strong correlation with MPs in tilapia and high salinity/EC.

Since eigenvalues sharply decline after PC3 and level off, thereby satisfying the Kaiser criterion (eigenvalues >1), Figure 7.4B, the corresponding scree plot, shows that the first three principal components are adequate for meaningful analysis, hence the 3D plot. In subsequent clustering and interpretation, this supports the retention of three components. With a significant spatial difference between upstream and downstream sampling sites, the PCA results collectively show that water chemistry, specifically salinity, EC, and TDS, significantly affects MPs' distribution across matrices.

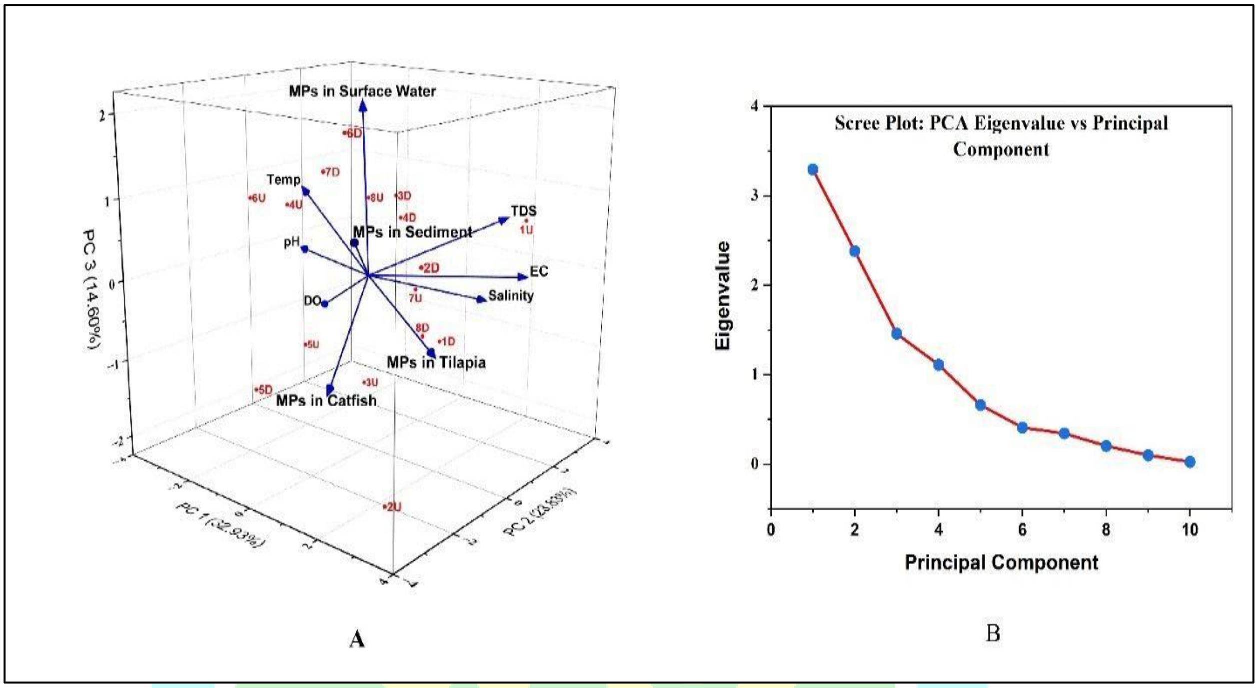


Figure 7.4: PCA of WQPs and microplastic concentrations in Lake Volta. (A) Threedimensional biplot of site distribution and variable loadings. (B) Scree plot showing variance explained by each principal component. D, downstream; U, upstream

7.3.5. Cluster Analysis

The first two principal components (PC1 and PC2) in Figure 7.5A show the results of a Kmeans clustering, which collectively account for 56.76% of the dataset's variance. Each of the three unique clusters is surrounded by a 95% confidence ellipse. According to the PCA biplot interpretation that associated MPs in surface water and temperature with PC2, and MPs in tilapia and EC with PC1, the division between these clusters represents fundamental variations in MPs concentrations and water quality profiles across sampling sites.

The hierarchical clustering dendrogram using Euclidean distance and Ward's linkage is displayed in Figure 7.5B. With distinct branching patterns that closely match the K-means assignments, the dendrogram also supports a three-cluster solution. While inter-cluster distances reflect wider ecological differences, sites grouped within the same cluster show minimal linkage distances, indicating strong internal similarity in MPs and WQPs.

These clustering analyses, when combined with the previous PCA result, confirm that the study sites can be categorised into different ecological regimes according to multivariate signatures. Cluster 2 is linked to higher MPs in surface waters, Cluster 3 to high MPs in tilapia and elevated EC and TDS levels, and Cluster 1 to higher sediment MPs and lower salinity. In MPs' monitoring initiatives, these clusters can be used as a basis for spatial risk classification and focused mitigation techniques.

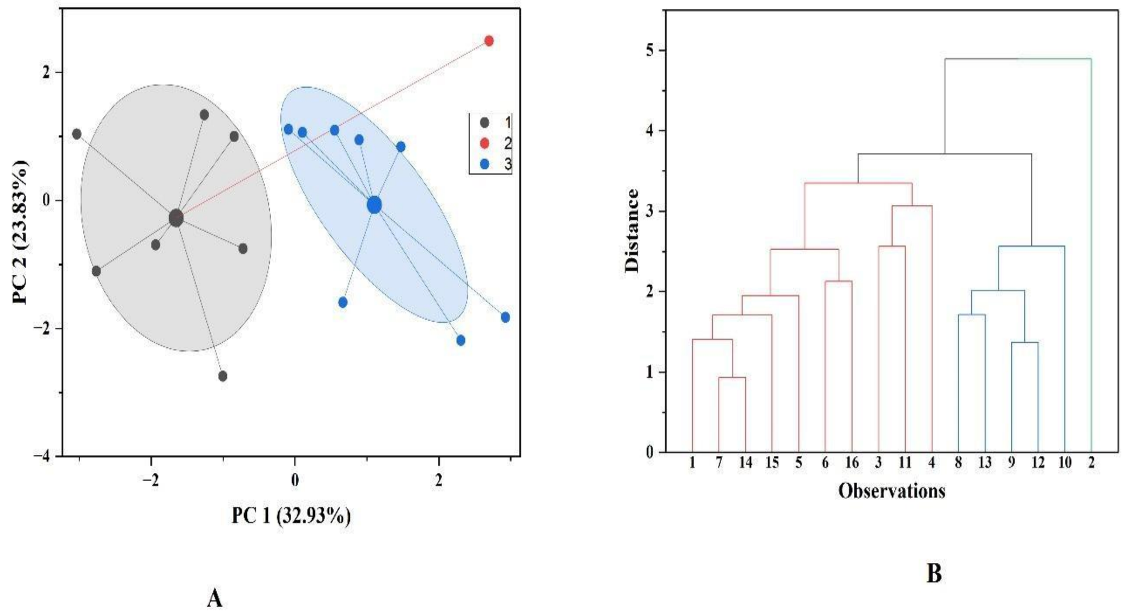


Figure 7.5: K-means clustering (A) and hierarchical clustering dendrogram (B) of WQPs, both resolving three site groupings.

7.4. Discussion

The physicochemical conditions of the study area indicate a relatively stable freshwater system, with most parameters falling within or close to WHO guideline values (WHO, 2017; Boamah et al., 2024). Temperatures were consistently warm (28.9–32.4 °C), providing favourable conditions for biological activity, well within the warm regime reported for Lake Volta in recent assessments by Elegbede et al. (2015) and Kodom et al. (2018) and typical of tropical Ghanaian lakes. The slightly elevated temperatures at Ayerifie Bator (4U) and Lonto (7D), compared to the cooler conditions at Akateng (1D), suggest localised influences, possibly linked to hydrodynamics, shading, or anthropogenic modifications such as cage culture (Osei et al., 2019). This aligns with the generally warm profile of tropical freshwater bodies, including those in Ghana such as the Lower Volta and Lake Bosomtwe, where high water temperatures stimulate metabolic and microbial processes (Owusu-Boateng et al., 2022; Kwakye et al., 2021).

The pH values largely reflected suitable conditions for aquatic life, though 13 readings above WHO limits for drinking water raise concerns about localised alkalinity (WHO, 2017). Sites such as Kitari (5U) and Accrape (8U), which recorded the highest pH values, may be influenced by agricultural runoff, effluent discharges, or natural buffering from carbonated-rich inflows, pattern consistent with precious assessments by Gampson et al. (2015) and Kwakye et al. (2021) which links physicochemical shifts to domestic and agricultural pressures. Similar elevated pH has been reported in parts of Lake Volta, particularly toward the southern basin and occasionally higher in inflowing tributaries, and basin syntheses for the White Volta Basin, often linked to nutrient enrichment from fertilizer use and domestic waste inputs (Mul et al., 2015). Notably, the pH values observed in this study is less than values reported by Orina et al. (2020) for Lake Victoria but higher than that of Elegbede et al. (2015) on Lake Volta. While alkaline waters are not inherently harmful, prolonged deviations from neutral conditions may affect species composition and physiological tolerance of aquatic organisms. Recent work within the Volta system (e.g., Kpong Headpond pH ~5.9–7.8) further supports a management focus on localised sources rather than basin-wide shifts (Boamah et al., 2024).

Conductivity and TDS levels confirmed the low ionic strength of the water system. Both parameters were well below WHO thresholds, pointing to limited salinity intrusion and low mineral content. These results highlight the freshwater nature of the system and its resilience against salinisation pressures, which is particularly important for inland fisheries. The result is consistent with previous work by Karikari et al. (2013) on Lake Volta which indicated that Lake Volta's value is the lowest value compared to Lake Bosomtwe and other inland waters. However, the higher values observed at Kotoso (1U) and Accrape (8U) may indicate localised solute enrichment, perhaps from domestic wastewater or agricultural sources, a phenomenon also reported in tributaries feeding into Lake Volta (Mul et al., 2015). The strong correlation between EC and TDS ($r = 0.874$, $p < 0.001$) in our dataset is indicative of shared ionic controls, aligning with hydrochemical studies showing that EC and TDS covary tightly in natural waters, with slope and strength depending on ionic composition (Taylor et al., 2018; Kwakye et al., 2021).

Dissolved oxygen (DO) levels showed more variability. While most sites-maintained concentrations within or slightly above WHO recommendations (8–10 mg/L), Atimpoku (2D) stood out with lower values (4.7–4.9 mg/L). This oxygen depletion may point to organic loading, reduced turbulence, or pollutant inputs in this locality just as predicted by Boamah et al. (2024) and Kwakye et al. (2021). Moreover, the boat cruising activities around the area could lead to sediment resuspension, releasing organic matter that consumes oxygen during decomposition (Sagerman et al., 2019). Since oxygen is a critical determinant of ecosystem health, the low DO values raise ecological concerns, especially regarding fish survival and microbial balance. In contrast, higher DO at Kitari (5U) likely reflects better reaeration and/or lower biochemical oxygen demand, a pattern consistent with reach-scale heterogeneity observed across the Volta system (e.g., recent Kpong Headpond mapping and Lower Volta bioassessment studies) (Boamah et al., 2024; Kwakye et al., 2021).

Spatial modelling provided further insights into cross-site variability, consistent with recent spatial analyses on Lake Volta's Kpong Headpond by Boamah et al. (2024), who mapped water-quality patterns using regression and satellite data to capture local heterogeneity. Exponential variograms best represented temperature, pH, and TDS, while the spherical and Gaussian structures were better suited for EC, DO, and salinity, a pattern coherent with geostatistical theory that smoother, slowly varying variables (e.g., temperature, pH) tend to exhibit stronger short-range spatial dependence and therefore higher kriging reliability, while more reactive variables (e.g., EC, DO) show higher prediction errors due to local drivers (Webster & Oliver, 2007). Importantly, temperature and pH were modelled with greater accuracy, whereas EC and DO show higher predictive errors, reflecting their spatial heterogeneity and sensitivity to local drivers. Together with evidence of reach-scale heterogeneity in the Lower Volta, these results indicate that some parameters display consistent spatial structure whereas others are more stochastic and locally forced, reinforcing the need for parameter-specific sampling densities and model diagnostics in Ghanaian freshwater monitoring (Kwakye et al., 2021).

Based on the cross-validation diagnostics, the performance of the fitted variogram models varied significantly across the measured water quality parameters. The Exponential model provided the best fit for Temperature (RMSE = 0.769, RMSS = 0.913), pH (RMSE = 0.325, RMSS = 0.821), and Total Dissolved Solids (RMSE = 2.757, RMSS = 0.793), indicating a well-calibrated estimation of uncertainty as the Root Mean Square Standardized (RMSS) values were close to the ideal value of 1.0. In contrast, the Spherical model applied to Electrical Conductivity resulted in a relatively high error (RMSE = 3.595) and a poorly calibrated uncertainty (RMSS = 0.524), suggesting the model did not adequately capture the spatial variance. The Gaussian model, used for Dissolved Oxygen and Salinity, yielded mixed results; while Salinity predictions were accurate (RMSE = 0.044, RMSS = 0.815), the model for Dissolved Oxygen produced the highest error (RMSE = 4.527) and a significantly miscalibrated uncertainty (RMSS = 2.138), where the average standard error (ASE = 4.664) substantially underestimated the actual prediction errors. The low sampling density likely necessitated the use of the more flexible Exponential and Gaussian models to fit the attenuated spatial structure, but the high errors and suboptimal RMSS values for key parameters like Conductivity and Dissolved Oxygen underscore the limitations imposed by data sparsity on model reliability.

Correlation analyses revealed that MPs in tilapia were negatively associated with pH and DO, suggesting that fish experiencing lower pH and oxygen levels accumulate more MPs. This may be due to physiological stress altering feeding/filtration and immune function, potentially increasing particle intake, effects documented for *Oreochtomis noliticus* under MP exposure and in MP, hypoxia interaction studies (Adeogun et al., 2020; Li et al., 2021). Interestingly, MPs in tilapia were strongly correlated with MPs in catfish, indicating shared exposure pathways and overlapping feeding niches, consistent with Ghanaian diet studies and Ghana freshwater MP surveys that report MPs in both fish types (Blankson et al., 2022; Mensah et al., 2019). However, most correlations with WQPs were weak or nonsignificant, aligining with recent study on Lake Volta where MP-sediment relationship were limited, implying multi-stressor, non-linear controls rather than single-parameter drivers. (Boateng et al., 2024).

Multivariate analyses helped structure this complexity. In the PCA, EC, TDS, and salinity loaded strongly on PC1, underscoring the role of solute/ionic dynamics in influencing MPs distribution, a result convergent with Lake Volta water-quality PCAs where ionic strength and solids dominate primary gradients (Tay, 2021). Biotic MPs (tilapia, catfish) separated from sediment and surface water MPs, indicating distinct exposure routes and compartmentalisation within the ecosystem. Similar PCA/HCA source-apportionment of MPs has been reported across West Africa's inland waters (Doherty et al., 2024; BruceVanderpuije et al., 2025). Clustering further resolved three site regimes in the data: (i) high sediment MPs/low salinity, (ii) elevated MPS in surface waters, and (iii) elevated tilapia MPs with high EC/TDS, echoing reach-scale heterogeneity observed for the Lower Volta and reinforcing parameter-specific monitoring needs (Kwakye et al., 2021). Taken together, while Lake Volta's overall physicochemistry remains broadly supportive of aquatic life, localised deviations (e.g., elevated pH at certain sites, low DO at Atimpoku, higher ionic loads at Kotoso/Accrape) appear to structure MPs patterns, supporting integrated, multi-metric monitoring frameworks and targeted interventions (e.g., focusing fish-contamination surveillance in high-EC zones) advocated in Ghanaian and regional assessments (Masiá et al., 2021).

7.5. Conclusion

Lake Volta's water quality is broadly supportive of aquatic life, characterised by low ionic strength and generally adequate dissolved oxygen; however, localised deviations, notably alkaline pH outliers, DO minima at Atimpoku, and elevated EC/TDS at Kotoso and Accrape, coincide with distinct microplastics signatures in water, sediment, and fish. The tight EC–TDS coupling and the negative associations of fish microplastics with pH and DO indicate multi-stressor controls rather than single-parameter drivers, while spatial modelling shows that some variables (temperature, pH) exhibit stable, predictable structure, whereas others (EC, DO) are heterogeneous and require denser sampling and rigorous model diagnostics. Accordingly, institutions in charge of the management of the water like fisheries commission should prioritise high-EC/TDS zones for fish-pollution surveillance, mitigate organic loading and boating-induced resuspension at sensitive shoreline sites (e.g., Atimpoku), and apply variogram-guided network design (kriging/cross-validation) to optimise station spacing by parameter, pairing routine physicochemical monitoring with microplastics assessment in biota and sediments to capture compartmentalisation. Future work should incorporate seasonal replication, polymer fingerprinting of microplastics, trophic-transfer metrics, and adaptive management for Ghana's inland fisheries. Also, the number of sampling points should be increased from the 16 communities to 30 to 60 points to ensure a better spatial interpolations and representation of the lake's spatial heterogeneity.

CHAPTER EIGHT

General Conclusion, Recommendations and Contribution of Research

8.1. Conclusion

Based on the comprehensive findings of this research, it is concluded that Lake Volta faces a significant and multi-faceted microplastic pollution challenge, driven primarily by anthropogenic activities. This study delivers the first comprehensive baseline for the dry season, quantifying average concentrations of 15.88 ± 10.69 MPs/L in surface water and 148.33 ± 119.35 MPs/kg in sediment, confirming the lake as a major sink with significant spatial variability. The investigation establishes that unsafe local waste management practices—with plastics constituting nearly 40% of household waste and open dumping (51.9%) as the dominant method—serve as the principal source of MPs entering the lacustrine system.

This contamination is not uniformly distributed; spatial analysis confirms the formation of significant MP hotspots, particularly in sediments, which act as the major environmental sink, and in surface waters, with patterns indicating downstream accumulation. Risk assessment reveals that surface waters present a higher immediate ecological risk (ERI: 30.52) compared to sediments (ERI: 27.44), while polymer hazard indices (PHI: 14.76 water, 13.02 sediment) underscore a persistent long-term threat.

Critically, the study confirms the bioaccumulation of MPs within the lake's ecosystem, as evidenced by their ingestion by economically vital fish species (2.47 ± 1.30 MPs/individual in tilapia; 2.29 ± 1.73 MPs/individual in catfish). The dominance of small-sized MPs (<50 µm) in biota indicates a high potential for trophic transfer, marking a direct pathway into the aquatic food web. Furthermore, the research identifies key environmental drivers, demonstrating statistically significant negative correlations between MP concentrations and fundamental water quality parameters, notably pH and dissolved oxygen, positioning MPs as an integrated component of the lake's environmental stress matrix.

In summary, the pollution in Lake Volta presents a compounded transboundary risk: it is sustained by identifiable local sources and knowledge-practice gaps, distributed into accumulating environmental reservoirs, assimilated into living organisms, and modulated by broader limnological conditions. Given the lake's regional significance, these interconnected findings underscore the urgent need for targeted waste management interventions, continued ecological monitoring, and the development of integrated policies that address both the source of plastic pollution and its multifaceted impacts on freshwater resources, fisheries, and dependent communities across the basin.

8.2. Recommendations for Mitigating Microplastic Pollution in Lake Volta

To mitigate the rising threat of microplastic (MP) pollution and safeguard Lake Volta’s ecological and socio-economic functions, a multifaceted and evidence-driven approach is required. The recommendations span six thematic areas including solid waste management, monitoring and research, analytical techniques, policy and governance, community engagement and education, and nature-based/technological solutions. These actions are intended to reduce plastic leakage into the lake, strengthen institutional capacity, improve analytical accuracy, and promote long-term sustainability through both technological innovation and community participation. For each action, lead institutions have been identified to ensure accountability and effective implementation. The table below integrates key actions, expected outcomes, and responsible institutions.

Thematic area	Key Actions	Expected Outcome	Lead Institution

Solid Waste	Expand recycling; replicate composting facilities (e.g., Dambai); develop biodegradable fishing nets and packaging	Reduced plastic leakage into Lake Volta; increased recycling and composting; sustainable alternatives embedded in local economies.	Ministry of Works, Housing, and Water Resources (MWHWR); Ministry for Local Government, Chieftancy and Religious Affairs (MLGCRA); MMDAs; Zoomlion Ghana Ltd. And other private waste firms
Monitoring and Research	Institutionalise routine MP monitoring in water, sediment, and fish; increase research funding into MP; apply	Reliable, comparable MP datasets; improved detection of denser polymers; better understanding of seasonal dynamics.	Water Research Institute (CSIR-WRI); Universities (UENR; UG, KNUST, UDS; UCC); Environmental

	higher-density separation ($NaI/ZnCl_2$); conduct seasonal replication.		Protection Agency (EPA)
Analytical Techniques	Invest in advanced FTIR and micro-FTIR; foster crossdisciplinary R&D collaborations; complement FTIR with Raman or pyrolysis-GC/MS for enhanced polymer identification.	Higher sensitivity and accuracy in MP identification; comprehensive polymer characterization; improved reproducibility of results.	University and CSIR laboratories; Ghana Standards Authority (GSA); International research collaborations

Policy and Governance	Strengthen enforcement of plastic disposal regulations; equip Environmental Health Officers with adequate	Improved compliance with plastic waste management laws; strengthened institutional capacity; regionally	Parliament of Ghana; EPA; MWHWR; MLGCRA; Volta River Authority (VRA); ECOWAS bodies
	funding and authority; provide affordable alternatives to single-use plastics; harmonise policies across Lake Volta riparian states; ban the use of singleuse plastics	aligned pollution control measures; use of biodegradable packages	

Community and Engagement Education	Need for robust curriculum integration of WASH; run solid waste management campaigns; incentivise gear recovery.	Long-term behavior change; increased public participation in waste management; reduced fishing-gear-related plastic inputs.	Ghana Education Service (GES); MLGCRA; National Commission for Civic Education (NCCE); Fisheries Commission; Local fisherfolk associations

Aside the above captured recommendations, it is recommended that anyone who may want to advance this research should consider considering all seasons to know the real picture of the menace. Additionally, there should keen interest to increase the number of sampling station to help in getting the best out of the spatial models.

8.3. Contribution to Knowledge

This dissertation makes several distinct and substantive contributions that advance the understanding and management of microplastic (MP) pollution, with specific progress beyond the current state of knowledge as articulated in the following points:

1. Filling a Critical Regional and Methodological Gap
    a. It provides the first comprehensive, multi-matrix (water, sediment, biota) assessment of MPs for Lake Volta and, more broadly, for a major West African freshwater system. This directly addresses a critical data scarcity,

establishing foundational, decision-ready baseline concentrations (e.g., 15.88 ± 10.69 MPs/L in surface water) where previously only limited or inferred data existed.

   b. Methodologically, it extends the application of ATR-FTIR for polymer identification in complex freshwater matrices within a data-poor region, critically evaluating its operational strengths and limitations (e.g., sensitivity constraints for particles <50 µm) to inform future methodological choices in similar contexts.

2. Advancing Spatial and Source Attribution Understanding

   a. This research pioneers the integration of field-collected MP data with spatial modelling (ArcGIS) to not only map contamination hotspots but also statistically link them to identifiable local anthropogenic drivers (fishing intensity, shoreline waste practices). This moves beyond mere concentration reporting to provide a spatially explicit model of source-tosink relationships in a large lacustrine environment.

3. Quantifying Socio-Ecological Linkages and Knowledge-Practice Gaps

   a. It empirically links household waste management practices—quantifying plastic waste composition (~40%) and dominant disposal methods (51.9% open dumping)—directly to in-lake MP loads. Furthermore, it identifies and measures a specific socio-behavioral paradox: high general awareness of environmental harm (90.6%) coexists with low practical waste segregation knowledge (40%) and minimal e-waste awareness (26.2%), providing quantitative evidence of a critical knowledge-practice gap that must be addressed for effective intervention.

4. Refining Ecological Risk Assessment in Freshwater Systems
    a. The study establishes statistically significant relationships between MP abundance and key water quality parameters (notably negative correlations with pH and dissolved oxygen), contributing to the understanding of MP as a component of environmental stress.
    b. It provides a comparative ecological risk assessment, demonstrating that while sediments are the major long-term sink, the immediate ecological risk is higher in the surface water column (Ecological Risk Index: 30.52 vs. 27.44). This nuanced finding offers crucial insight for prioritizing monitoring and remediation efforts.
    c. It delivers species-specific bioaccumulation data for economically vital fish (tilapia, catfish), confirming fibre and polyethylene dominance and indicating no significant interspecies difference in exposure within this ecosystem, a key finding for food web and fisheries risk assessments.
5. Delivering a Contextualised and Actionable Policy Framework
    a. Beyond generic recommendations, the dissertation produces an institutionspecific actionable framework, directly linking prescribed actions to mandated agencies (EPA, MSWR, Fisheries Commission, etc.). This strengthens the science-policy interface by providing a transferable model for translating research findings into governance and management actions within the Ghanaian and similar institutional contexts, thereby contributing concretely to SDGs 3, 6, and 14.

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APPENDIX I

Ethical Clearance

UNIVERSITY OF ENERGY AND NATURAL RESOURCES, SUNYANI
COMMITTEE FOR HUMAN RESEARCH AND ETHICS

OUR REF: CHRE/AP/173/2024

DATE: January 25, 2024

Applicant
Collins Nana Andoh

Department of Civil and Environmental Engineering

UENR

Dear Applicant,

LETTER OF APPROVAL

Protocol Title: **Spatial Modeling of Microplastics Concentration in Lake Volta**
Proposed Site: Volta Lake and surrounding municipal assemblies
Sponsor: Principal Investigator

Your submission to the Committee on Human Research and Ethics on the above - named protocol refers. The Committee has considered the ethical merit of your submission and has approved the protocol. The approval is for a fixed period of one year, beginning January 2024 to January 2025 renewable thereafter. The Committee may however, suspend or withdraw ethical approval at any time if your study is found to contravene the approved protocol.

Data gathered for the study should be used for the approved purposes only and should adhere to the provision of the Ghana data Protection Act, **Act 843 2012**. Permission should be sought from the Committee if any amendment to the protocol or use, other than submitted, is made of your research data.

The Committee should be notified of the actual start date of the project and would expect a report on your study, annually or at the close of the project, whichever comes first. It should also be informed of any publication arising from the study.

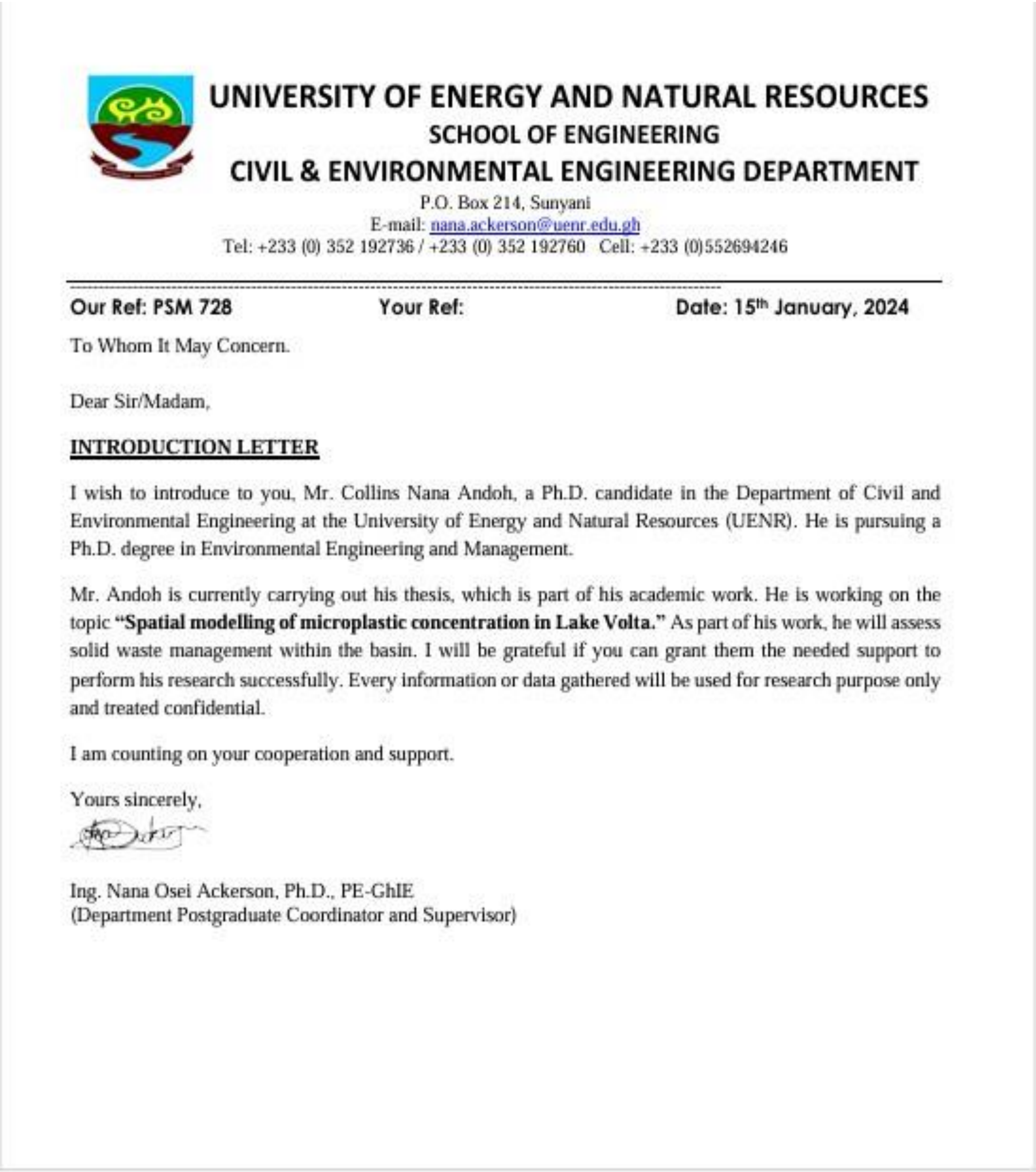
Thank you for your application.
Yours faithfully,

Prof. Samuel Fosu Gyasi
Chairman

UENR Official

APPENDEX II

Introductory letter



UNIVERSITY OF ENERGY AND NATURAL RESOURCES
SCHOOL OF ENGINEERING
CIVIL & ENVIRONMENTAL ENGINEERING DEPARTMENT
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Our Ref: PSM 728 **Your Ref:** **Date: 15th January, 2024**

To Whom It May Concern.

Dear Sir/Madam,

INTRODUCTION LETTER

I wish to introduce to you, Mr. Collins Nana Andoh, a Ph.D. candidate in the Department of Civil and Environmental Engineering at the University of Energy and Natural Resources (UENR). He is pursuing a Ph.D. degree in Environmental Engineering and Management.

Mr. Andoh is currently carrying out his thesis, which is part of his academic work. He is working on the topic **"Spatial modelling of microplastic concentration in Lake Volta."** As part of his work, he will assess solid waste management within the basin. I will be grateful if you can grant them the needed support to perform his research successfully. Every information or data gathered will be used for research purpose only and treated confidential.

I am counting on your cooperation and support.

Yours sincerely,

Ing. Nana Osei Ackerson, Ph.D., PE-GhIE
(Department Postgraduate Coordinator and Supervisor)

APPENDIX III

Sample Collection Tools

A. Household Questionnaire

Questionnaire for Survey on Solid Waste Management

(Households)

This questionnaire is part of a PhD study on microplastics in Lake Volta and seeks information on how your household stores, separates, and disposes of waste, and on the services available in this community, to help reduce plastics entering the lake and improve waste management. The interview takes about 15–20 minutes. Participation is voluntary; you may skip any question or stop at any time. There is no payment and no penalty for not taking part. No names are recorded and responses are kept confidential and analyzed in aggregate. With your permission, the interviewer will briefly inspect your waste container (e.g., bin or sack) to confirm the main type of waste; no photographs will be taken without consent. The eligible respondent is the household head or another adult knowledgeable about household waste practices; interviews with minors occur only with parent/guardian consent and the minor's assent. This study has ethics approval from the Committee for Human Research and Ethics of the University of Energy and Natural Resource.

Demographics

1. District/Municipality……………………………………………………………
2. Neighborhood/locality …………………………………………………………..
3. Age………………………
4. Gender
    a. Male
    b. Female
5. Educational Qualification of the head of household (HH)
    a. Illiterate
    b. Basic education
    c. Secondary education
    d. Tertiary
6. Profession of the head of HH
    a. Government employee
    b. Private employee
    c. Trading
    d. Retired
    e. Fisherman
    f. Farmer
    g. Others, specify……………….
7. HH family size…………………………….

Awareness

8. Do the local authorities organise an awareness programme regarding household solid waste management? Y/N
9. Do you know the effects of improper waste management? Y/N
10. Do you know the principles of waste characterization? Y/N
11. Do you know about the segregation of waste? Y/N

12. Do you think segregation of waste is important in the household? Y/N
13. Are you aware of electronic waste? Y/N
14. Do you know the principle of solid waste minimization? Y/N
15. Are you committed to minimizing waste? Y/N **Plastic Waste Management**
16. What (category of) waste is dominant in your daily HH waste?
    a. Organic wastes
    b. Plastic waste
    c. Paper waste
    d. Metals
    e. Textiles
    f. Wood
    g. Glass and ceramics
    h. Others
17. What is the volume of waste your household generates daily?
    a. Less than or equal to 1.0 kg
    b. 1.1 to 2.0 kg
    c. 2.1 to 3.0 kg
    d. Above 3.0 kg
18. What percentage of the waste generated at your home is plastic?
19. Who disposes of your HH waste?
    a. Servant
    b. Family Member
    c. Another Person
20. Where is the HH waste disposed of?
    a. In the dustbin
    b. By roadside
    c. In a space near the house
    d. Door-to-door waste collectors of the Assembly
    e. Designated Refuse dump site
21. How much are you currently spending on waste disposal per month?........................
22. How often do you dispose of your HH waste?
    a. Everyday
    b. Once every week
    c. Once every month
    d. Others, specify………….
23. How do you dispose of your HH waste in
    a. Polythene/ plastic bag
    b. Small bucket
    c. Waste management company's dustbin
    d. Any other container
24. Generally, when do you dispose of your waste?
    a. No definite time

    b. 6 am to 6 pm
    c. After 6 pm

25. Which system do you prefer for the removal of your HH waste?
    a. A collector will collect the waste from the house
    b. The collector will come to a certain place at a certain time to take the waste from you
    c. You will dispose of the waste in the dustbin
    d. You will keep your waste container at a certain time by the roadside for the collector to pick it up
26. Do you know where the HH waste is taken? Y/N
27. Satisfaction level about the present municipal waste removal system
    a. Very Satisfied
    b. Satisfied
    c. Okay
    d. Dissatisfied
    e. Very Dissatisfied
28. Do you agree that if waste is not disposed of properly, it can pollute the environment? Y/N
29. Do you know of a company that buys plastic wastes?
30. Have you ever sold plastic waste before?

‘

B. Interview Gude for informants

INTERVIEW GUIDE FOR SOLID WASTE MANAGEMENT ASSESSMENT (INFORMANTS)

1. District:…………………

2. Locality:………………

3. Age:………………………

4. Gender:…………………….

5. Portfolio in the town:………………….

6. How does your locality dispose of their household waste?

7. Is there any specific use of the collective waste in your locality?

8. How many waste collection points do you have in your locality?

9. What are the institutions responsible for waste collection in your locality?

10. What significant effect has the presence of Municipal/District Municipal waste caused in your locality?

11. How often does the District/Municipal waste management team visit your locality for waste collection and disposal?

12. How can you rate the waste management situation in your locality?

13. How often does environmental sanitation (Cleanup exercise) occur in your locality?

14. Who initiates the cleanup exercise?

15. Do you take part of the exercise?

C. Envrionmental Officers Interview Guide

A STRUCTURED INTERVIEW GUIDE FOR SOLID WASTE MANAGEMENT SERVICE SURVEY

(DEPARTMENT OF ENVIRONMENTAL HEALTH AT THE ASSEMBLY)

This questionnaire is designed to facilitate the assessment of the current situation of solid waste management services in districts and municipalities of the communities along the Volta Lake that are earmarked for sampling purposes. The information collected will help know the exact situation on the grounds and its correlation with the number of microplastics that will be identified at the sampling stations. It is a PhD research work and hence confidentiality will be paramount. Confidentiality is highly respected.

1. District/Municipality responsible for the solid waste management

………

2. Area of jurisdiction

Urban area………. (sq. km)

Rural area………. (sq. km)

Total area……….. (sq. km)

3. Population

The population of Community of interest………………………………

Urban Population……………………

Rural Population………………………

Total Population………………………

4. Name, address, and telephone of the Department responsible for waste management

……..Telephone……………………………………………………………………………

5. How many contractors does this department work with in managing solid waste?
6. Kindly mention them

……………………………………………………………………………………………

…………………………………………………………………………………
……………………………………...………………………………………
……………………………………….

7. Function carried out by the Department

Functions	**Carried Out By**			**Remarks**
	Own Self	**Contractor**	**Others, please specify**	
Solid waste management service to domestic premises				
Solid waste management service to commercial/trade premises				
Solid waste management service to industrial premises				
Street sweeping				
Grass cutting				
Drain/river cleansing				
Public toilet cleansing				
Removal of dead animals				
Removal of garden waste				
Removal of bulky waste e.g., TV				

Removal of abandon vehicles				
Development/Building plan approval				
Procurement of vehicles/equipment				
Maintenance of vehicles and equipment				
Recruitment of solid waste management staff				
Training in solid waste management staff				
Public Education				
Special solid waste management campaign/project				
Others				

8. If data on waste characteristics are available, please complete the following table:

Component	**Community of interest**		**Municipality/District**	
	Volume (Kg)	**%By Weight**	**Volume (Kg)**	**%By Weight**
Paper				
Plastic and rubber				
Organic or vegetables				
Glass and ceramic				
Metal				

Wood				
Textile				
Others				
Total				

9. Year when the data was collected:
10. Was the data collected by actual survey or by estimation?..
11. Does the department have a storage bin standardization policy? If so, please briefly outline the policy:

……………………………………………………………………………………………………
……………………………………………………………………………………………
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……………………………………………………………………………………………
…………………………………………………………

12. Type of storage bin used (please tick appropriate space)

Types of Containers		**Residential Premise**				**Commercial Premise**			
		A	**F**	**S**	**N**	**A**	**F**	**S**	**N**
Individual Container	Metal bin								
	Plastic bin								
	Plastic bag								
	Oil drum								
	Others								
Commercial Containers	Metal bin								
	Plastic bin								
	Oil drum								
	Concrete bin								

	Roll-on rolloff								
	Others								

A = Almost exclusively used, F = Frequently used, S = Sometimes used, N = Never used

13. Collection service coverage for domestic premises for this year

	% of Total Population	**Frequency of Collection**
Urban Population		
Rural Population		

14. Collection service coverage for commercial/trade premises for this year

	% of premises	**Frequency of Collection**
Collected by the Department		
Collected by the Department's contractor		
Collected by owner's contractor		
No collection service (done by owner)		

15. Amount of waste collected (by both the Department and contractors) this year

Waste Type	**Estimated Recycling Rate (%)**	**Amount Calculated**			
		Measured	**Estimate**	**Measured**	**Estimated**
Domestic, institutional, commercial and trade waste					

Industrial waste					
Street/park cleaning waste					
Bulky waste					
Others					
Total					

Note: An attempt should be made to provide the breakdown data. If possible, at least data for the total should be provided.

16. Disposal

Items	**Disposal Site**		
	Site 1	**Site2**	**Site 3**
Name of site			
Total area (ha)			
The year when disposal started			
Estimated life span remaining (year)			
Amount of waste deposited daily (tonne/day)			

Distance from collection area to the site (km)			
Disposal method (see notes below)			
Existence of animals on site	Yes/No	Yes/No	Yes/No
Existence of pickers and scavengers on site	Yes/No	Yes/No	Yes/No
The existence of open burning on-site	Yes/No	Yes/No	Yes/No

Note: For disposal methods, please specify as follows

O = Open dumping

C = Controlled tripping (with occasional soil cover)

S = Sanitary landfill (with daily cover)

D = Dumping into a water body (river/sea etc.)

17. Are the disposal sites in the localities close to water bodies? Y/N
18. Are there any means or strategies put in place to prevent solid waste from entering surrounding water bodies? If yes, specify……

19. Are there mechanisms to eliminate solid wastes that get into water bodies?
20. Problems encountered in solid waste management services. Please tick the appropriate space.

Problem	**Very serious**	**serious**	**not so serious**	**no problem**
Inadequate service coverage (some people are not given service)				
Lack of service quality (not frequent enough, spill, etc.)				
Lack of authority to make financial and administrative decisions				
Lack of financial resources				
Lack of trained personnel				
Lack of vehicles				
Lack of equipment				
Old vehicle/equipment frequent breakdown				
Difficult to obtain spare parts				
Lack of capability to maintain/repair vehicle/equipment				
No standardization of vehicle/equipment				
No proper institutional set-up for solid waste management service				
Lack of legislation				

Lack of enforcement measures and capability				
Lack of planning (short, medium, and long-term plan)				
Rapid urbanization outstripping service capacity				
Uncontrolled proliferation of squatter settlements				
Difficult to locate and acquire landfill site				
Difficult to obtain cover material				
Poor cooperation by Government agencies				
Poor public cooperation				
Uncontrolled use of packaging material				
Poor response to waste minimization (reuse/recycling)				
Lack of qualified private contractors				
Difficult to control contractual service				
Lack of control on hazardous waste				
Others				

APPENDIX IV

Gallery

Field Work

A picture with Chief of Kafaba, Kafabawura Seidu Yahaya as part of

community entry

In situ sampling of Water Quality Parameters

Sediment sampling with van Veen grab at Kpebe

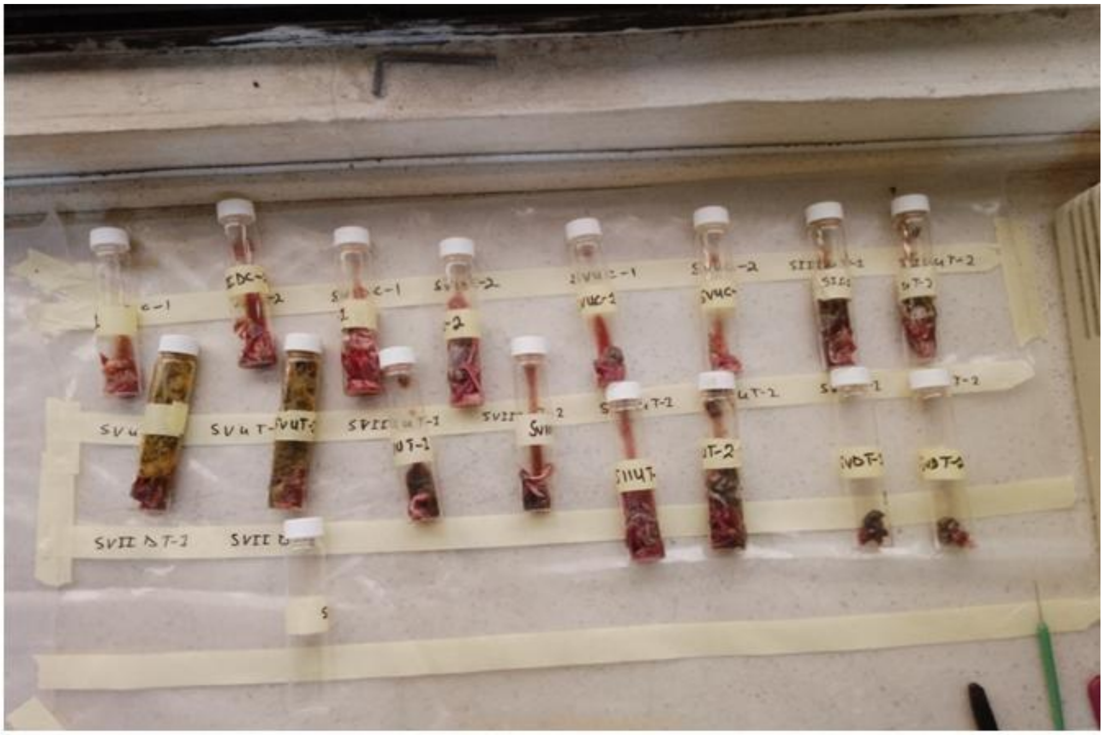
A visit to Dambai IRECOP facility

Laboratory Work

Fish specimen for laboratory analysis

Water and Sediment samples for laboratory analysis

Fish dissection in section



Fish guts and gills ready for digestion with KOH

Rotation of samples to get rid of saponification

Samples ready for identification

Identification in process