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MICROPLASTICS IN FRESHWATER ECOSYSTEMS AND ITS ENVIRONMENTAL IMPLICATIONS: THE CASE OF THE ODAW RIVER IN GHANA.

BY

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DECLARATION

I, Millicent Amekugbe, hereby declare that except for references to other people's works, which I have duly acknowledged, this thesis is the result of my independent research conducted at the Institute for Environment and Sanitation Studies, College of Basic and Applied Sciences, University of Ghana, Legon, under the joint supervision of Prof. Chris Gordon, Dr. Ted Annang, and Dr. Daniel Nukpezah. I also declare that, as far as I know, this thesis has neither in part or in whole been published nor presented to any other institution for an academic award.

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ABSTRACT

In Ghana, escalating plastic waste has amplified microplastic pollution in the environment. The Odaw River in Accra, an urban waterway grappling with sanitation issues, has become increasingly polluted, necessitating and investigation on microplastics in this ecosystem. Despite various pollutant studies in the river, microplastics have been largely unexplored. To address these issues, this study investigates the occurrence of microplastics and their interactions (including mesoplastics) with heavy metals in the Odaw River while assessing the impact of behavior and risk perceptions regarding plastic use. Water and sediment samples were collected from 16 sites along the Odaw River. Samples were then analysed in the lab through various process; digestion, density separation, filtration and identification. Microplastics were examined under a microscope to determine their abundance, types and spatial and temporal distribution. Polymer identification was conducted through Fourier Transform Infrared Spectroscopy (FTIR) analysis, and the ecological risk of these microplastics was assessed using ecological risk indices like the pollution load index and polymer hazard index. To examine the interaction between heavy metals and microplastics, heavy metal concentrations were measured from samples of micro/ mesoplastics and sediment samples collected from seven locations along the river and analyzed for heavy metals using the aqua regia method and Atomic Absorption Spectroscopy (AAS). Ecological Risk indices were also used to assess the level of pollution of the Odaw River with heavy metals. Quantitative and qualitative survey methods were employed to gather data from respondents in four communities along the river. This data aimed to understand their behavior regarding plastic use, plastic waste management, risk perception, and knowledge about microplastics, with questionnaires serving as the primary research instrument. In the study's findings, microplastic particles were found in both water (14 - 56 items per liter) and sediment (12 - 60 items per 50 grams) at all sampling sites along the Odaw River. The highest abundance in MPs in surface water was located at Korle Gonno (Estuary) (55.33 items/l), and that for sediments was at Agbogbloshie (61.00 ±11.17 items/ 50g). The lowest concentrations of MPs were recorded at the source of the Odaw River in Brekusu (Brekusu 2) (14.00 ± 1.89 items/l; 12.00 ± 1.90 items/50g) in water and sediment samples, respectively The concentration of microplastics was more significant during the wet season compared to the dry season. Fiber-shaped microplastics were the most common, making up 73.4% of the samples, with sizes between 1000-3000 µm being the most abundant. Polyethylene was the predominant polymer, accounting for 48% of all particles. Pollution Load Index (PLI) and Polymer Hazard Index scores were remarkably high, particularly downstream. The average concentrations of heavy metals (Pb, Cu, Fe, Zn, Cr, and Hg) in meso/microplastics were higher than in the sediments. Pollution indices like Igeo, CF, and PLI were generally relatively low. The study underscores the importance of considering factors such as behavior, risk perception, plastic waste management, and microplastic knowledge in addressing excessive plastic usage. Respondents were aware of the adverse environmental and health effects of plastics, yet the use of plastics, including single-use plastics, persisted. In essence, addressing the challenges posed by plastic pollution in the Odaw River necessitates a comprehensive strategy that encompasses individual accountability, industry standards, effective monitoring, cooperative initiatives, innovation, regulatory measures, incentives, and heightened consumer awareness. By tackling each of these components, we can collaboratively strive for a future characterized by reduced plastic consumption and a diminished impact of plastic pollution on our environment.

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LIST OF ABBREVIATIONS

AB	Agbogba
AC	Achimota
AG	Agbogbloshie
AK	Abokobi
AL	Alajo
AMA	Accra Metropolitan Assembly
AV	Avenor
BOD	Biological Oxygen Demand
BPA	Bisphenol A
BR1	Brekusu 1
BR2	Brekusu 2
CCME	Canadian Council of Ministers of the Environment
CF	Contamination Factor
CFA	Confirmatory Factor Analysis
CHR/HAA	Christan Village / Haatso
CV	Christian Village
CY	Cosway
DDT	Dichlorodiphenyltrichloroethane
DOM	Dissolved Organic Matter
DPSIR	Drivers Pressures State Impact and Response
EDC	Endocrine Disrupting Chemicals
EF	Ecological Risk Factor

FIA-AAS	Flow Injection Analysis - Atomic Absorption Spectrophotometer
FTIR	Fourier Transform Infrared Spectroscopy
GAMA	Greater Accra Metropolitan Area
GNPAP	Ghana National Plastic Action Partnership
HA	Haatso
HDPE	High-density Polyethylene
IG	ICGC
IR	Ecological Risk Index
Igeo	Geoaccummulation Index
KG	Korle Gonno
KMP	Knowledge of Microplastics
KU	Kuotam Estates
LDPE	low-density polyethene
MESTI	Ministry of Environment Science Technology and Innovation
MMDAs	Metropolitan Municipal and District Assemblies
MMPs	Meso/ microplastics
MPs	Microplastics
NOAA	National Oceanographic and Atmospheric Association
PA	Polyamide
PAHs	Polycyclic Aromatic Hydrocarbons
PB	Pro-environmental Behaviour
PBDEs	polybrominated diphenyl ethers
PCBs	Polychlorinated Biphenyls
PE	Polyethene

PES	Polyester
PET	polyethylene terephthalate
PEVA	polyethylene-vinyl acetate
PLI	Pollution Load index
PMMA	Poly Ethyl Methyl Methacrylate Acrylic
POM	Polyoxymethylene
POP	Persistent Organic Pollutants
PP	Polypropylene
PS	Polystyrene
PT	Pantang
PU	polyurethane
PUB	Plastic Use Behaviour
PVC	Polyvinyl chloride
PWM	Plastic Waste Index
RI	Risk Index
RIP	Risk Perception
SDG	Sustainable Development Goal
SEM	Structural Equation Model
SEM-EDS	Scanning Electron Microscopy-Energy Dispersive Spectroscopy
SUP	Single Use Plastics
TE	Teiman
VROM	Dutch Target and Intervention Values
WHO	World Health Organisation

CHAPTER ONE

INTRODUCTION

This first chapter gives a background to the entire study; it discusses plastics, specifically microplastics, in aquatic environments. This study is divided into three categories, each elaborated in this chapter to highlight their importance and the central problem. Furthermore, the chapter also presents the aims and specific objectives and rational of the study. Concluding this chapter is the organisational structure of the thesis.

1.1 Background

1.1.1 Freshwater Ecosystems and Plastics

Freshwater ecosystems are vital in the survival of humans and are key in the global water cycle. They are also home to diverse organisms (Matthews, 2016). Freshwater systems such as lakes, rivers, springs, wetlands, ponds and streams provide ecosystem services that support human well-being; such as provisioning services, which include water use for domestic activities, transportation and hydropower. (Aylward *et al*., 2005). However, climate change and population increase, which have led to urbanisation and growth in other anthropogenic activities, threaten freshwater quality and quantity (Fitzhugh & Richter, 2004). Specific threats to these ecosystems include chemicals from industries, agriculture runoffs, household wastes, overexploitation of groundwater and invasive species (Matthews, 2016). A substantial contaminant of concern to the environment is plastics. Plastics are everywhere in our environment due to the inefficient management of plastic waste (Rochman, 2018).

1.1.2 Plastics as Emerging Threats

"Plastics" is a commonly used term encompassing a diverse array of synthetic or partially synthetic materials that find extensive and continually expanding usage across various applications (Gareiou et al., 2022). "Plastic" is derived from the Greek word "plastikos," which means to mould. The word plastic relates to the substance's intrinsic malleability and plasticity throughout the production process, which enables the plastic to be shaped, pressed, moulded into a variety of forms, including but not limited to films, fibres, plates, tubes, bottles, boxes, and many other configurations (Kent, 2007). According to the International Organisation for Standardisation (ISO), plastic is a "*material which contains as an essential ingredient a high molecular weight polymer and which, at some stage in its processing into finished products, can be shaped by flow*" (ISO, 2013).

Plastics, known for their remarkable versatility, are well-suited for a broad spectrum of consumer and industrial uses. Their relatively low density provides the advantage of lightweight products. Additionally, plastics exhibit corrosion resistance, ensuring durability in harsh environments. Some variants are transparent, facilitating the creation of optical devices (van Oosten, 2022). The flexibility of plastics to be moulded into intricate shapes enables the integration of other materials, making plastics suitable for diverse functions. The adaptability of plastics allows the development of plastics with a wide array of properties, making them applicable to various purposes. These qualities of plastics have led to their use in construction, agriculture, health care, electronics, food packaging etc. (Garcia-Garcia et al., 2022).

Plastics, however, have become a threat to the environment due to their constant use and disposal into the environment (Derraik, 2002; Peng et al., 2020). The negative impacts of plastics have a significant effect on freshwater ecosystems (Azevedo-Santos et al., 2021). Even though the use of plastics has its societal benefits, it poses a threat to the environment due to its widespread and waste management (Wagner *et al*., 2014). Due to their durability and resistance to degradation, plastics persist in the environment (land, water and air) for an extended period, causing an accumulation of plastics in the environment, especially compounded by poor waste management (Rochman, 2018).

Plastics form approximately 60-80 per cent of litter produced globally (Derraik, 2002). When exposed to environmental conditions, plastics disintegrate into smaller fragments (meso, micro and nanoplastics) (Horton *et al*., 2017). Plastics are classified into several categories. A widely utilized classification structure is based on size, employing prefixes like macro, meso, micro, and nano to categorize plastics (Qi et al., 2020). Macroplastics are defined as plastic particles of sizes greater or equal to 2cm, mesoplastics size range within 5mm-2cm, microplastics range within 1mm-5mm in size, and nanoplastics are less than 1µm in size (Berenstein *et al*., 2023).

According to GNPAP (2021), approximately 0.84 million tonnes of municipal solid waste plastics were generated in Ghana in 2020. Furthermore, around 0.08 million tonnes of plastic find their way into aquatic ecosystems, such as lakes, rivers, streams, and the marine ecosystem, constituting approximately 9.5% of the plastic waste produced. Many households' resort to utilizing open storm drains to discard their waste (GNPAP, 2021), a problem exacerbated by the presence of informal settlements along major rivers and some stormwater channels. These informal settlements often lack basic amenities and access to municipal solid waste collection services, leading them to rely on rivers and drains as their primary disposal sites. The issue of plastic waste in Ghana presents a prevalent and multifaceted problem that affects various ecosystems throughout the country. Rivers, in particular, play a significant role in exporting microplastics thus exacerbating the harmful consequences of plastic pollution by carrying this waste into the sea (Peng et al., 2020).

1.2 Microplastics (MPs)

Microplastics (MPs) are tiny plastic particles whose longest diameter range from greater than 0.1 mm to less than 5 mm (Akdogan & Guven, 2019). Primary and secondary sources make up the two main sources of microplastics. Microplastics of primary origin are intentionally made as tiny particles, typically within specific size ranges. These particles are deliberately incorporated into various products, including cosmetics, cleaning agents, and medical products. (Horton *et al*., 2017). On the other hand, secondary plastics originate from fragmentation of larger plastics under physical, chemical, and biological processes resulting in fragmentation into smaller pieces. Exposure of these MP polymers such as polyacrylonitrile, polyvinyl chloride and polymethyl methacrylate (Yuan *et al.*, 2022) as well as additives such as Polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecanes (HBCDs) used in the production process of plastics have harmful impacts on organisms in the environment (Wang *et al.*, 2017).

Large amounts of MPs are found in the marine ecosystem, from beaches to the water column and sediments. Microplastics can also be found in waste waters, surface waters and estuaries (Rochman, 2018). Primary MPs, mainly polyethene, polystyrene and polypropylene, particles in cleaning and cosmetic products, enter the aquatic environment through household sewage discharge (Horton *et al*., 2017). Other primary MPs come from industrial raw materials such as plastic resin powders or pellets. Although countries, including Ghana, and some European and North American countries, have banned cosmetic products containing primary MPs due to their adverse environmental effects (Ballent *et al*., 2016), these microplastics are still found in the environment.

The amount of microplastics in the environment is thought to be mostly caused by secondary microplastics. Microplastics can be found in environmental samples in a variety of shapes and forms, including pellets, threads, filaments, and fragments, due to the distinct sources (ocean and land-based) and abrasive mechanisms involved in their formation (Cole et al., 2011).

1.2.1 Microplastics in Freshwater Ecosystems

Several investigations have been conducted on the vital subject of plastics and microplastics in the marine environment (Eriksen *et al*., 2014; Auta *et al*., 2017; Amelia *et al*., 2021; Haque & Fan, 2023). Plastics and microplastics (MPs) can enter the marine ecosystem through a variety of sources and pathways, such as transmission via rivers and the atmosphere, beach littering, and direct entry at sea through aquaculture, shipping, and fishing (GESAMP, 2016). According to Lebreton *et al*. (2016), rivers are a major source of plastic pollution into the ocean, with an estimated 1.15 to 2.41 million tonnes of plastic debris from rivers entering the water each year.

The most intricate mechanism for the movement and retention of MPs is found in freshwater environments, such as wetlands, rivers, and streams (Horton *et al*., 2017). They serve as pathways for microplastics to enter the marine ecosystem and take in MPs from the terrestrial environment (Beaumont et al., 2019). By shattering bigger plastics, known as macroplastics, with pressure and other abrasive processes applied to plastics, they also function as a technique of producing microplastics. According to Kooi *et al*., (2017), freshwater habitats have the potential to act as sinks by holding microplastics in sediments. As a result, microplastics have varied impacts on aquatic fishes and other organisms; ingesting these microplastics has negatively impacted the growth of some fish species (Cannon *et al*., 2016; Foley *et al*., 2018). Numerous studies have demonstrated the ingestion and buildup of microplastics in marine organisms, with a focus on fish species like mackerel (*Scomber japonicus*) and other organism such as copepods (*Calanus helgolandicus*) (Haque and Fan, 2023). The accumulation of microplastics within these organisms can adversely affect their health, leading to issues such as stunted growth, infertility, and hindered egg hatching. Humans may also ingest MPs via the food chain transmission, which could harm human health (Bhuyan, 2022). As opposed to marine ecosystems, freshwater environments are crucial to human existence, yet our understanding of the effects of microplastic contamination in freshwater environments is still in early stages (Talbot and Chang, 2022).

Furthermore, the physical and chemical characteristics of MPs allow them to adsorb other pollutants onto their surfaces and act as carriers for contamination of organisms after ingestion are also an important cause for concern (Carbery *et al*., 2018). Microplastics pose increasingly concerning ecotoxicological risks in aquatic environments. According to Sutherland *et al*., (2010) and Auta *et al*., (2017), microplastics are contaminants of emerging concern in the ecosystem that may have an impact on human capacity to preserve biodiversity.

The Odaw River serves as a source of livelihood for individuals living along the river. Research on the effects of microplastics on this freshwater ecosystem will be helpful in identifying potential risks to the environment and the welfare of the surrounding populations.

1.3 Problem Statements

Plastic debris (macro, meso and microplastics) can directly affect animals by inducing physical and chemical toxicity and indirectly by changing habitat properties and transporting pathogens and invasive species (Prata *et al*., 2020). Plastic pollution can have multiple socio-economic impacts, ranging from direct financial losses in various sectors to decreased ecosystem services that entail indirect costs (Kumar *et al.*, 2021). Also, plastic pollution carries aesthetic and ethical problems, which are difficult to quantify yet relevant (D'souza *et al*., 2020).

In recent years, Ghana has witnessed a notable increase in the presence of plastic waste within its overall waste composition, with the proportion rising from roughly 3% in 1994 to around 14% in 2014 (Miezah *et al.,* 2015). This substantial surge in plastic waste is a consequence of changing product packaging trends, with more consumer products now being packaged in plastic materials, resulting in plastics becoming ubiquitous in the environment. Nukpezah et al. (2022) have noted that plastic litter has become the most prevalent and diverse form of litter found in coastal environments in Ghana. Significantly, plastic items can break down and potentially serve as a source of secondary microplastics in riverine ecosystems. However, it is important to recognize that there is a lack of comprehensive studies that have systematically measured the levels of microplastics in these ecosystems in Ghana.

The presence of microplastics in the freshwater ecosystems such as the Odaw river is harmful to the health of the ecosystem and this in turn affects other ecosystems such as lagoons, coastal and marine ecosystems into which these freshwater rivers empty into (Jambeck, 2015). The presence of microplastics is harmful to organisms that inhabit such ecosystems (Wagner & Lambert, 2018). For instance, microplastics are transported into the sea and are eaten by some organisms in the sea such as fishes, these fishes end up on our tables and without careful post preparation on these fishes, we ingest them and these may have harmful health effects for us. The Odaw river, for example which enters the sea at through the Korle Lagoon transports huge amounts of plastic to the beaches and then into the sea (Pinto *et al.*, 2023). There have been instances where majority of catch by fishermen in this area have had more plastic components in their nets than fish. Fishermen have had to sort out the small number of fish from plastic litter. These challenges call for a thorough study into the effects of these plastics and microplastics in the freshwater ecosystem.

Microplastic research has been focused extensively on the marine ecosystem (Cole *et al.*, 2011; Wang, 2023). However, it was not until the early 2000s that studies in freshwater environments became an area of concern (Wagner & Lambert, 2018). Microplastics have been present in the environment for a long time and are regarded as contaminants of emerging concern (CEC). CECs encompass a wide range of pollutants that have occurred in water sources only recently, or they have garnered attention due to being detected at unexpectedly elevated concentrations, and their potential risks to human and environmental health may not be comprehensively grasped (Pastorino and Ginebreda, 2021).

Freshwater ecosystems serve as either transport pathways where microplastics move from terrestrial environments to other aquatic ecosystems and eventually to the marine ecosystem or as sinks where microplastics accumulate in sediments (Wagner *et al.*, 2014). Approximately 70-80% of marine litter are plastic, originating from inland waters, which transport it into the ocean (Wagner *et al.*, 2014). There are several ways by which microplastics enter freshwater ecosystems: i) through runoffs from stormwater, ii) from wastewater treatment plants, iii) atmospheric deposition and iv) release from industrial processes (Klein *et al*., 2018).

Although data on the levels of MPs in Ghana is very limited, some studies indicate that rivers transport about 1.5-2.5 million tonnes of MPs into the oceans annually (Geyer et al., 2017). Lechner *et al*. (2014) provide initial findings from the Danube River which indicate that substantial quantities of microplastics; about 4.2 tonnes of MPs per a day are transported by major rivers, thereby significantly contributing to marine plastic pollution. Mani *et al*., (2015) also reported that the Rhine River contains an average of 892,777 particles/ km ^{2} of microplastics, with plastic fragments accounting for 60% of the total MP. These studies indicate that just as reported for marine ecosystems, freshwater ecosystems may be conduits and sinks for MP from source to marine environments, deserving further investigation.

Microplastics Occurrence

The abundance, distribution and types of MPs have been studied in several ecosystems and major rivers in the Europe and Asia, including the Thames, Danube, Yangtze, etc. (Kicošev & Galambos, 2022:Whitehead *et al*., 2021; Wu *et al*., 2018). Because microplastics persist in the environment, their number is expected to grow exponentially with decreasing size (Cózar *et al*., 2014; Kooi *et al*., 2017). Therefore, unless appropriate mitigation measures are implemented, MPs abundance is expected to increase considerably in the future (Pan *et al*., 2019). Factors such as population density, urbanisation and industrialisation within catchment areas, and rainfall rates affect the abundance and types of MPs transported into the ocean (Lebreton *et al*., 2017). Hence the need to assess the occurrence of MPs in freshwater environments especially urban rivers like the Odaw River

Microplastics Interaction with Other Pollutants

The interactions between microplastics and hazardous substances is a cause for concern (Wang *et al.,* 2017) and is harmful to subsequent exposure to organisms that ingest them (Bakir *et al*., 2014). Studies reveal that microplastics can concentrate polychlorinated biphenyls (PCBs), Polycyclic aromatic hydrocarbons (PAHs), and Dichlorodiphenyltrichloroethane (DDT), which are examples of hydrophobic organic contaminants increasing the bioavailability of these toxins to organisms (Rochman et al., 2013). Heavy metals are also known to physically or chemically bind to the surfaces of microplastics. Heavy metal pollution in rivers and its subsequent adsorption onto microplastics are traced back to human activities such burning waste, disposing of waste, burning wood, applying pesticides, smelting, and emitting brake pad emissions from vehicles. (Liu et al., 2021). The metal enrichment burden varies across microplastic types (foam, hard fragments, pellets) (Agboola and Benson, 2021). Many factors, such as the type of polymer, the additive profile, the source of the emissions, previous exposure, residence time, surface area, degree of surface erosion and weathering, and variations in biofouling rates, can contribute to the accumulation of heavy metals on microplastics (Patterson et al., 2020). According to Agboola and Benson (2021), these variables lead to an increase in the variations in the metal adsorption pattern on microplastics.

Social Interactions with Plastics

Human behaviour is a fundamental area of study needed in resolving plastic pollution, especially to promote sustainable use rather than solely relying on traditional methods of focusing on economic incentives and disincentives (Jia *et al*., 2019;). In addition, the current focus on and perception of the harm posed by plastic pollution has increased interest in researching how social interventions can change people's attitudes and behaviour towards the environment (SAPEA, 2019).

While public opinions of plastics have significantly changed in Western industrialised societies from favourable to hostile, developing nations in Asia and Africa have not yet experienced this shift (Zen *et al*., 2013). Due to the public's heavy reliance on plastics, public opinion in developing nations is still positive or, at most, undifferentiated (Stoler *et al*., 2012).

Environmental risk perception involves an individual's understanding of the importance of environmental protection and the relationship between people and the environment (Zeng *et al*., 2020). It influences people's willingness to engage in environmentally friendly actions. When individuals perceive high environmental risks, they are more likely to change their behaviours and lifestyles to be more environmentally conscious (Liu *et al*., 2021). Pro-environmental behaviour includes a range of eco-friendly actions, from product choices to more general behaviours like seeking environmental information, participating in environmental activities, conserving energy, and practising waste separation (Minelgaitė and Liobikienė, 2021). Behavioural change in plastic waste management is critical to solving the plastic waste menace. According to Heidbreder *et al.* (2019), one of the least understood and most challenging aspects of plastic's ecological impact is its disposal.

Ecological Risk

To ensure ecosystem safety, there is a need to measure the ecological risk of certain substances introduced into the environment. Ecological risk assessment seeks to evaluate the effects of stressors on the local environment (He and Huang, 2020). Fundamentally, ecological risk assessment estimates the risk from chemicals in the environment. Ecological risk has expanded recently to include the wide range of stressors facing ecological receptors (Newman *et al*., 2022).

Although the information on microplastic management is scarce, there has been concern over the ecological risk of microplastics among regulators and researchers (Koelmans *et al*., 2014). The ecological risk assessment of MP pollution in the aquatic environment is poorly understood (Mehinto et al., 2022).

Generally, reasons such as microplastics occurrence, microplastics interaction with other pollutants and social interactions with microplastics underscores the pressing need for additional research to gain a better understanding of the extent and consequences of microplastics in Ghana's aquatic ecosystems. The presence of these minuscule plastic particles can have significant ecological and environmental repercussions, making further investigations essential to develop effective strategies for addressing the growing challenge of microplastic contamination in the country.

1.3.1 Study Area Concerns

1.3.1.1 The Urban River (Odaw River)

The Odaw River originates from the Eastern Region of Ghana on the Akuapem- Togo range and passes through periurban and urban areas of Greater Accra. The Odaw Basin comprises the Korle Lagoon, the Odaw River, and its tributaries. It is one of several rivers in the Greater Accra Metropolitan Area (GAMA), making it an urban river system. Land use in the catchment of the river includes industrial, residential and agricultural activities. Although the Odaw River serves mainly as a drainage system for the central part of Accra (Larmie, 2019), it also serves as a source of livelihood, as the river is used for irrigating farmlands and supports various economic activities, including car washing in the upstream and mid-stream regions areas.

1.3.1.2 Anthropogenic Activities, Pollution and Sanitation Challenges along the Odaw River

Upstream of the Odaw River comprises less populated settlements, making the pressure and activity around the river at that section less intense. The river course upstream is relatively clean and is used for the irrigation of farms and also for other activities such as washing cars, etc. The mid and upstream areas consist of residences and a few farmlands. Due to waste management challenges some communities face along the river, portions of the river have been turned into dumping areas for garbage (Karikari *et al.*, 2009). In addition, farming activities along the river and other fertiliser residues that seep into the water channel are sources of nutrients that are introduced onto the river (Ntajal *et al.*, 2022).

Pollution from activities from densely populated towns surrounding the drain/channel is a threat to the Odaw River and Korle Lagoon downstream. Several anthropogenic activities occur along the basin, but of importance is what happens downstream, which is Accra's central business and industrial hub. Over 80% of industries in the Greater Accra Metropolitan Area (GAMA) are located within the Odaw catchment (Lamie, 2019). In addition, some markets and retail shops are situated along the river's course. Along the Korle Lagoon is the core site for scrap dealers, other auto-mechanic shops, and refrigerator repair shops also line up within the Korle Lagoon catchment. These businesses and activities along the watercourse introduce pollutants into the river due to unsustainable methods, such as waste disposal into the river body, especially by scrap dealers processing their wares (Ntajal *et al.*, 2022).

The Odaw River has been obstructed in some places by plastic debris, weeds, and shrubs, and culverts and drains have been weakened by erosion (Karikari *et al*., 2009). In the city's centre, where there are shops, marketplaces, eateries, and truck parks, stagnant bad waters can be found in the drains (Larmie, 2019). Due to improper maintenance, undersized culverts overpassing highways, flow obstacles from utility and service lines, and unauthorised buildings inside the flow path, several aspects of the channel are in poor condition (Larmie, 2019).

Pollution is a severe problem in the Odaw River basin because it is surrounded by industries, urban settlements, and agricultural farmlands that produce waste and drain sewage into the basin (Ntajal *et al*., 2022). Oil spills, solid trash, e-waste, untreated sewage, and soil erosion are just a few of the many issues the Odaw River faces. According to some research (Kyere *et al*., 2016; Fosu-Mensah *et al*., 2017; Adomako and Dellor, 2023) heavy metal contamination levels and distribution indicate that heavy metals pose a serious hazard to the Odaw River Basin. There is very little biological life in the Korle Lagoon due to widespread contamination (Ansa *et al.*, 2017).

Despite the contamination of the Odaw basin with plastics (Pinto *et al.*, 2023), comprehensive research on the amounts of microplastic pollution have not been conducted. Hence, there is a need to determine the abundance, types and distribution of microplastics along the river basin. Knowledge of microplastics in the river basin will help determine how measures can be implemented to reduce and remove these plastics from the aquatic ecosystem. Monitoring and managing the channels via which microplastics enter the hydrosphere depends critically on the identification and quantification of microplastics in the aquatic ecosystem.

The Odaw basin has been extensively studied on land use, land cover, E-waste pollution, flooding, heavy metal pollution and others (Ackom et al., 2020a; Ansah et al., 2020; Dodd et al., 2023; Oteng-Ababio, 2012). This river basin has been successively reported to be polluted with toxic organic or/and inorganic pollutants, some of which were demonstrated to pose risks to aquatic organisms and even humans (Ansa *et al*., 2017). Nevertheless, the pollution status of these emerging pollutants of concern - microplastics within the Odaw basin and even most freshwater bodies in Ghana, is still unclear presently.

Hence, this study investigated the abundance of MPs, their distribution and morphological characteristics in the Odaw River. The study also examines the interaction of microplastics with other elements in the river. This study is necessary as interactions with other factors significantly impact the stability and sustainability of the freshwater ecosystem. Additionally, to avoid the "silo perspective" of the research, considering the interactions of MPs with other pollutants, such as heavy metals in the ecosystem, will extensively elaborate on the dynamics likely to occur within the system.

In curbing the menace of plastic pollution in society, some aspects of behaviour need to be understood. Hence, this research will seek to determine the drivers of plastic pollution within the communities that live along the catchment and their risk perception of plastics and MPs.

1.4 Research Questions

The overarching question this study seeks to address is;

- *Is there a link between anthropogenic plastic input and microplastics occurrence and interactions in the Odaw River?*

To address this, further sub-questions to be considered are,

1. What is the abundance, distribution and types of MPs present in the Odaw River in Ghana?
2. Are there seasonal variations in the abundance, distribution and types of MPs present in the river?
3. How do MPs interact with heavy metals in the river and what is the associated ecological risk?
4. What are the drivers of plastic use within the communities along the river?
5. What is the risk perception of plastics to those living along the Odaw River?
6. What is the ecological risk assessment of MPs in the river?

1.5 Aim and Objectives

To provide answers to these research questions, this study generally aims to;

Investigate the occurrence and interactions of microplastics (and mesoplastics) with heavy metals in the Odaw River and assess the role of behaviour and risk perception on plastic use among communities around the river.

To investigate the aim of this study further, the specific objectives have been put into three categories;

Microplastic Occurrence

1. Identify the abundance, distribution and types of microplastics in the Odaw river

2. To evaluate the seasonal variation in MP load within the river

3. Assess the ecological risk of microplastics in the Odaw river

Microplastics Interaction with Heavy Metals

4. Determine the heavy metal content in sediments and micro/mesoplastics within the river.
5. Assess the ecological risk of heavy metals in sediments along the river.

Social Interactions

6. Investigate consumer behaviour in plastics use and waste management along the Odaw river.
7. Determine the knowledge and risk perception of people to plastics and MPs along the river river.
8. Determine the relationship between plastic use behaviour, plastic waste management, risk perception and knowledge of MPs.

1.6 Relevance of Study

There is a paucity of knowledge regarding microplastic pollution for different aquatic habitats, despite the fact that numerous studies have been conducted on the origins and effects of microplastics in the ocean (Green *et al.*, 2016 & Desforges *et al.*, 2015). (Horton *et al.*, 2017 & Wagner *et al.*, 2014). According to Dris *et al.* (2015), plastics originate in terrestrial settings and proceed via aquatic environments before entering the oceans. Microscopic plastics' physical and chemical characteristics need to be well described in order to comprehend their influence on the aquatic biota.

The Odaw Basin is of economic importance to the country as it provides water and is also one of the primary sources of livelihood as it is used for irrigating farms close to the river and is used by locals who stay upstream and midstream of the river for other economic benefits (Ntajal et al., 2022). Therefore, studying the impacts of plastics in this water body in Ghana will be of immense importance to the nation by providing evidence and serving as a reference for critical policy decisions regarding plastic pollution. This study can also be used as a blueprint for monitoring and evaluation of MPs in other freshwater ecosystems in the country.

The Sustainable Development Goals (SDGs) of the United Nations are an international initiative to eradicate poverty, safeguard the environment, and guarantee that everyone can experience peace and prosperity. These goals comprise 17 broad objectives to be accomplished by 2030 (SDGs, 2015). Microplastics in freshwater environments are relevant to multiple Sustainable Development Goals (SDGs). They impact clean water and sanitation (SDG 6) by affecting water quality and ecosystems. They have an adverse effect on terrestrial ecosystems, which is related to life on land (SDG 15), as well as aquatic life and biodiversity, which is in line with life below water (SDG 14). Microplastics have the potential to penetrate the food chain and affect human health as well as impact wellbeing (SDG 3). Reducing microplastics is in line with sustainable production and consumption (SDG 12). Collaborative partnerships are crucial (SDG 17) to address this issue. Overall, microplastics in freshwater environments have broad implications for sustainable development goals related to the environment, health, and responsible consumption.

One of the main focuses of the Sustainable Development Goals (SDGs) 2030 is the use and management of plastics, including MPs (Walker, 2021). In the context of the United Nations Sustainable Development Goals (SDGs), the issue of marine (micro)plastics has gained international attention under Goal 14, which is centred around the preservation and sustainable use of oceans, seas, and marine resources for sustainable development (de Sousa, 2021). More specifically, by 2025, Target 14.1 aims to prevent and significantly reduce marine pollution through all available channels, especially that which originates from land-based activities and includes nutrient and marine debris pollution.

1.7 Thesis Organisation

This thesis comprises six chapters; the first chapter introduces the study with the background and problem statement, research objectives, and relevance. Then, the study is categorised into three major sections regarding the objectives:

- Occurrence
- Interactions with Heavy Metals
- Social Interactions

Chapter 1 provides background information, outlines the rationale for the research, defines the study's aims and objectives, and highlights its significance and relevance.

Chapter 2 is an extensive review of literature relevant to the study regarding the three sections. Reviewed topics include the abundance, types and distribution of freshwater systems and microplastics, interactions of microplastics with biotic and abiotic elements and the social perception of plastic use and risk. In addition, this chapter elaborates on existing literature on behaviour theories used in the study of behaviour and risk perception.

Chapter 3 gives details about the study's materials, methodology, and study region. It also evaluates the occurrence, interactions with heavy metals, and societal interactions with plastics. The main study area and the several sampling points used in each study category are detailed in detail in this chapter.

Chapter 4 presents the study's findings in the three categories into which the specific objectives have been grouped (Occurrence, Interactions with heavy metals and Social interactions).

Chapter 5 Discusses the study's findings, the abundance and distribution of microplastics and the interaction of microplastics with heavy metals and sediments. The social interactions of plastic use and the risk perception of individuals who reside along the river catchment are also discussed. Plastic waste management and knowledge of microplastics is also addressed in this chapter.

Chapter 6 summarises the study's findings, conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

Literature related to the study is reviewed in four main sections. The first introductory section describes the links between freshwater ecosystems, plastics and microplastics. The second, third and fourth sections review three categories into which the study is designed i) Occurrence, ii) Interactions with heavy metals and iii) Social interactions. Finally, the chapter concludes with sections stating the research gaps discovered with the literature review and the study's conceptual framework.

2.1 Introduction

2.1.1 Freshwater Ecosystems and Plastic Pollution

Healthy and functional surface freshwater ecosystems such as rivers, lakes, streams, wetlands etc., provide ecological services for human wellbeing. Ecosystem services are defined as "*The conditions and mechanisms by which natural ecosystems, as well as the species comprising them, provide for and support the well-being and survival of human life.*" (Daily 1997; Millenium Ecosystem Assessment Report, 2005). These services fall under four categories: cultural, regulating, supporting, and supplying. Freshwater ecosystems offer economically significant commodities and services to civilization through their ecological services. A few of the services offered include animal and plant habitat (Hanna *et al.*, 2018), food and other marketable products (Hossu *et al.*, 2019), flood control, human and industrial waste purification (Hossu *et al.*, 2019), transportation, recreation (Baron & Poff, 2004; Aylward *et al.*, 2005; Thiele, 2020) and mitigation of the impacts of climate change through carbon storage (Vári et al., 2021).

However, anthropogenic activities have greatly influenced the conditions of freshwater ecosystems worldwide due to increasing populations, resulting in physical alteration by dams and the extensive human transformation of land cover. Other impacts include loss of habitat, extraction of water, pollution, excessive exploitation, and introduction of non-native and invasive species all contribute to the decreasing quantity and quality of freshwater ecosystems (Revenga *et al*., 2005). Climate change and other drivers, such as excessive nutrient flow into freshwater ecosystems from sources such as industries and sewage treatment plants, have also negatively affected freshwater ecosystems (Russi *et al*., 2013). Other pollutants of emerging concern, such as plastics, have also been identified as causing alterations in the freshwater ecosystem, affecting both hydrology of the river and organisms (Kramm *et al*., 2018).

With dwindling freshwater sources, it has become eminent to sustain healthy freshwater ecosystems to support human well-being (Baron & Poff, 2004). Consequently, with the benefits and value of freshwater ecosystems to human wellbeing, coupled with the high cost and difficulty of restoring degraded ecosystems, there has been growing awareness of water research and management (Bernhardt *et al*., 2005).

Plastics and Freshwater Ecosystems

Humans' excessive consumption of plastic products and it’s subsequent ineffective waste management has caused an exponential increase in the amount of plastics in freshwater (Tavengwa *et al*., 2022). As a result, surface freshwater ecosystems serve as conduits and sinks for the transportation of plastics into the marine environment, causing more harm to organisms in these ecosystems and eventually having negative impacts on human health (bioaccumulation along the food chain and economy, i.e.

causing obstruction to vessels transporting essential goods) (Kooi *et al.*, 2017; Beaumont *et al.*, 2019).

Plastics also interact with other pollutants in the ecosystem. According to ecotoxicology research, there are two means by which MPs can interact with other pollutants: hydrophobic pollutant adheres to the MP (Guo *et al.*, 2019) making them more bioavailable causing toxicity to organisms and other pollutants are absorbed into microplastics (Naqash *et al.*, 2020). Furthermore, plastic degradation would release additives or plasticizers that might be transmitted to living organisms. As an emerging pollutant, plastics are primarily not included in the water management process and hence are not monitored to ensure that these are controlled (Gaur *et al.*, 2022).

2.1.2 Plastic Size Classification

Understanding the relationship between the size of plastic particles, their surface area-to-volume ratio, and their interactions with hydrophobic contaminants is crucial for assessing the environmental and ecological consequences of plastic pollution (Atugoda *et al.*, 2021). Surface area-to-volume ratio increases significantly as the size of a particle becomes smaller. This phenomenon is particularly relevant when discussing the behavior of microplastics and nanoplastics in the environment. The increased surface area relative to volume has several important implications, especially regarding the adsorption of hydrophobic contaminants (Cássio *et al.*, 2022).

There is no agreement on categorising plastic debris, which may lead to additional uncertainties (Hartmann *et al.*, 2019). While some variables can be taken into account when classifying plastic particles, including chemical composition, condition, solubility, form and structure, colour, and provenance (Frais & Nash, 2019; Hartmann *et al.*, 2019), plastic particle size is the most frequently used and reported nomenclature

(Hartmann *et al*., 2019; Kramm *et al*., 2018). According to Hartmann et al. (2019), there are only four size categories that have been proposed: macroplastics, which are larger than 1 cm; mesoplastics, which are in the range of than 5–10 mm; microplastics, which are sizes ranging from 1–5 mm; and nanoplastics, which are smaller than 1–1000 nm (subdivided into nanoplastics 1–100 nm and sub-microplastics 100–1000 nm). There is a large range of sizes among the groups, and the recommended cutoffs are based on a workable compromise that takes the most recent research into account (Hartmann et al., 2019). They do not, however, always correlate to a particular physical or biological characteristic.

Studies on the environmental effects and toxicology of plastic pollution are becoming more common (Beaumont *et al.*, 2019; Atugoda et al., 2021). Due to its potential significance in influencing how MP interacts with biota and behave in the environment, particle size has significant ecological implications (Setälä *et al*., 2014: Bermúdez *et al*., 2021). According to experimental laboratory research, zooplankton may easily consume MP particles (Setälä *et al*., 2014: Bermúdez *et al*., 2021). Nonetheless, it is currently difficult to compare the recent work on MPs with the existing literature on plankton studies due to a possible disparity in size class classifications.

2.2 Microplastics

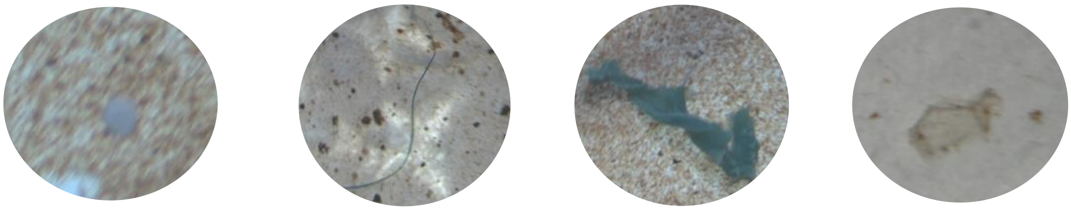
2.2.1 Characterisation of Microplastics *(Size, Shape and Polymer Type)*

The classification of microplastics and identifying their source depend on the morphological properties of these materials. The transport of microplastics in the environment are highly correlated with particle size. It also directly affects how easily microplastics enter organisms (Hidalgo-Ruz *et al*., 2012).

Microplastics are defined as plastic particles with a diameter smaller than 5mm, by the National Oceanographic and Atmospheric Association (NOAA). Researchers in the field frequently debate how to define the terms used to characterize microplastics in relation to size. There has been some variation in the minimum particle size threshold used to categorise MPs, with some writers classifying all particles less than 1 nm. With advances being made in the sampling and analytical procedures used, the sizes of microplastics are becoming more diversified and include a more comprehensive range.

Microplastics refers to any artificial solid particle or polymeric matrix with a regular or irregular form, insoluble in water, and a size range of 1 µm to 5 mm (Frais and Nash, 2019). The MP particle characterization describes the main chemical ingredient of the polymer (e.g., polyethylene, polystyrene, polyvinyl chloride, etc.). For cosmetics, for instance, primary MPs are created (GESAMP, 2015). Conversely, secondary MPs originate from the ongoing chemical and physical deterioration of bigger plastic particles found in the environment, including fishing gear or textile fibres (Frais and Nash, 2019).

Microplastics are described using several shapes such as fibres, fragments, films, beads (nurdles), foams and pellets. Individual studies describe fibres differently, they can be identified as single strands or as a bundle where individual fibres cannot be differentiated (Rochman et al., 2019). However, in general, they are thick, threadlike, and more than twice as long as they are thin (Cole et al., 2011). Broken off from more conspicuous plastic components, fragments are solid, angular, and asymmetrical pieces. Films are flat, relatively small bits that often form as plastic bags break down. Foams are frequently thick, soft, and compressible and can be angular or smooth. Tiny, vibrant pellets called nurdles are utilised in the production of plastic goods. They are typically round or cylindrical, smooth, and uniform. (Rochman *et al.*, 2019). The shapes and morphology of MPs are generally used as clues in identifying the source. For example, fibres are from clothes, upholstery wholes pellets are base materials used in industry, and beads are used to produce personal care products. Figure 2.1 shows the various shapes and morphology of MPs.



Bead **Fibre** **Fragment** **Film**

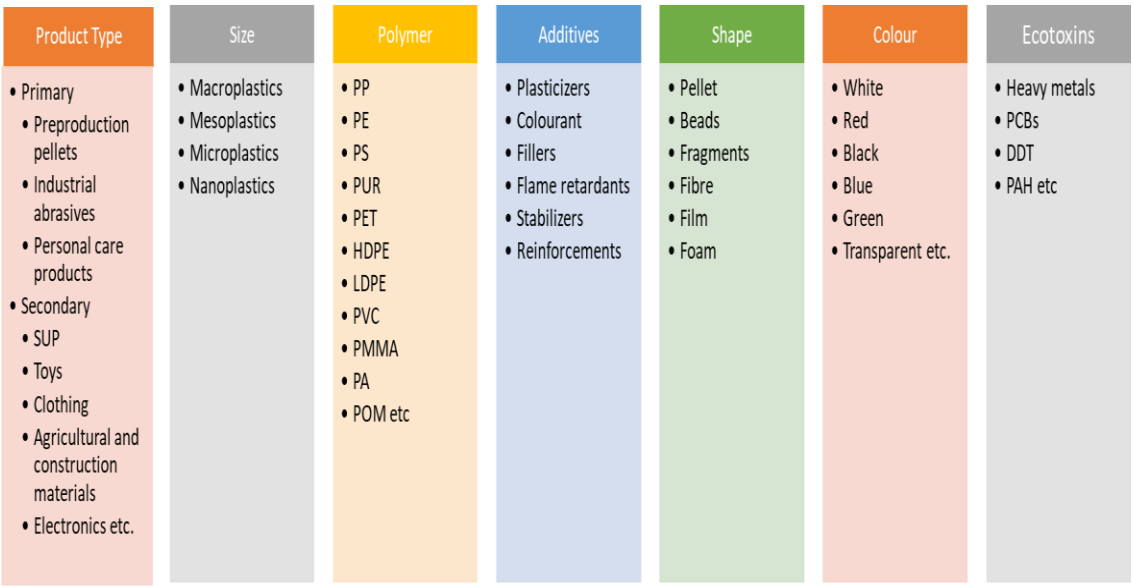
Fig. 2.1:Various Morphologies of Microplastics

Microplastics are not comprised of one unique substance but are a cocktail of various chemicals used in production. The most commonly used plastics and hence the most common polymer types of microplastics found in ecosystems PU (polyurethane), PS (polystyrene), PP (polypropylene), polyester (PES), PE (polyethylene), PA (polyamide, nylon), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (Jones et al, 2020, Plastics Europe, 2017). To satisfy the various applications for plastics, this range of polymers is necessary. For example, because PET is more durable than LDPE, it is used in water bottles. On the other hand, food packaging, film, and single-use grocery bags usually contain LDPE. In addition to bottles, PET is also produced into fibres that are used in the manufacturing of synthetic clothing (Rochman et al., 2019).

Jones *et al*., 2020 performed a systematic global data analysis and linked seven main types of MPs on land to those in the oceans, polypropylene, polystyrene, polyurethane, polyethylene terephthalate, polyethylene, polyvinyl chloride, and eclectic plastic. Unfortunately, the kinds of microplastics (MPs) found in aquatic ecosystems worldwide differ greatly throughout nations, and most research has focused on quantifying MP abundances with minimal evidence supporting any connections to MP sources.

It is essential to check plastics and the numerous chemicals used to enhance their functionality during production (additives). Among the additives that can help enhance the properties of plastics are flame retardants, plasticizers, antioxidants, light and heat stabilisers, acid scavengers, lubricants, antistatic agents and pigments (Almeida *et al.*, 2022). Bisphenols (Zhang *et al*.,2021), phthalates, and adipates are examples of representative plastic additives, and it is crucial to determine their toxicity and method of removal (Park & Park, 2021). In addition to the polymers from which plastics are made, organic compounds and trace metals from the environment are accumulated by microplastics (Rochman 2015). For instance, it is well recognised that heavy metals (like lead and copper) and persistent organic pollutants (like DDT, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons) can be absorbed via microplastics. In addition, MPs desorb additives into the environment, causing harm.

Rochman et al., 2019, illustrates the various forms of characterising MPs (polymers, size, colour , morphology, additives etc) in figure 2.2.



Product Type	Size	Polymer	Additives	Shape	Colour	Ecotoxins
• Primary • Preproduction pellets • Industrial abrasives • Personal care products • Secondary • SUP • Toys • Clothing • Agricultural and construction materials • Electronics etc.	• Macroplastics • Mesoplastics • Microplastics • Nanoplastics	• PP • PE • PS • PUR • PET • HDPE • LDPE • PVC • PMMA • PA • POM etc	• Plasticizers • Colourant • Fillers • Flame retardants • Stabilizers • Reinforcements	• Pellet • Beads • Fragments • Fibre • Film • Foam	• White • Red • Black • Blue • Green • Transparent etc.	• Heavy metals • PCBs • DDT • PAH etc

Fig. 2.2: Characterisation of Microplastics (adapted from Rochman et al., 2019)

2.2.2 Sources and Transport of MPS

Microplastics originate from two sources, primary sources and secondary sources. Primary microplastics are produced and used as tiny particles with a diameter of less than 5 mm (Akdogan & Guven, 2019). Examples of primary microplastics are beads used in manufacturing abrasives, capsules and microbeads used in personal care products and feedstocks, as well as resin pellets used as the base for manufacturing other plastic products (Lechner *et al*., 2014).

Secondary microplastics are created from the damage or fragmentation of bigger objects such as plastic litter, bottles, bags, packaging, fishing nets, synthetic bags, etc. through abrasion, delamination, or weathering (Rochman *et al*., 2019). Wastewater treatment, biological activities, and other environmental factors such as thermal or chemical stress, air oxidation, sunlight leading to UV degradation, and physical or mechanical forces all lead to disintegration and fragmentation (Andrady *et al*., 2003; Lambert, 2013).

Most plastic waste is not recycled and hence ends up in the environment, posing a significant hazard to wildlife (Geyer *et al*., 2017). Annual plastic pollution entering the world's oceans ranges from 4.8 to 12.7 million tonnes (Lebreton *et al*., 2017). The majority of the microplastics in the oceans come from rivers. The source of about 70–80% of the pollution in the ocean (Lebreton *et al*., 2017). The world's ocean is thought to contain 5.25 trillion MP and nanoplastics (Eriksen *et al*., 2014). Figure 2.3 illustrates the sources and pathways of plastics from land to ocean.

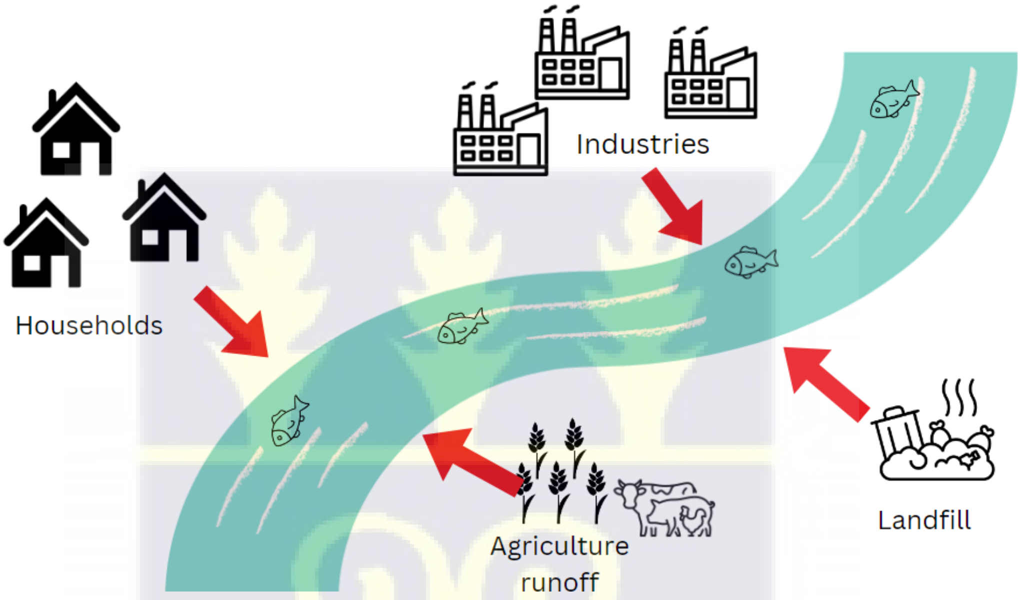


Fig. 2.3: Microplastic source contamination pathway (adapted from Park & Park, 2021)

There are various sources of microplastic pollution in freshwater ecosystems. According to Wang *et al*., 2021, geographical location (Sighicelli *et al*., 2018), human activities (Kataoka *et al*., 2019), and seasonal variation all have a significant impact on MP pollution (Rodrigues *et al*., 2018). Microplastic pollution in freshwater environments is from point sources such as industrial waste or spillage, household waste, or from nonpoint sources such as runoffs (Browne, 2015, Horton *et al*., 2017).

According to studies by Siegfried et al., sources of MPs in European rivers range from personal care items, laundry, household dust, tires, and road wear (Siegfried *et al*., 2017). Many cosmetics and personal care items contain tiny plastic microbeads that are often used for exfoliation or as additives. These microbeads can be washed off during use and eventually find their way into wastewater systems, ultimately reaching rivers (D'Avignon *et al*., 2022). The wear and tear of vehicle tires on roads is a less obvious but substantial source of microplastic pollution in rivers. As tires degrade, they release small rubber particles and microplastics, which are subsequently washed into stormwater drains during rainfall and eventually reach river systems (Järlskog *et al*., 2022). Another significant contributor to microplastic pollution in rivers is laundry. Cleaning synthetic fabrics, such as polyester and nylon, release microfibers into the washing machine's wastewater (Browne, 2015; Peng *et al*., 2017). When the washing process in a typical home washing machine was reproduced in a lab, many fibre-like microplastics were found in the washing machine's drainage (Hernandez *et al*., 2017). MPs have also been found in purified water and this may be caused by the deterioration of plastic equipment used for transportation or water purification (Mintenig *et al*., 2019).

Microplastics may enter rivers and lakes by surface runoff and air deposition (Dris *et al*., 2017). One example is the high concentration of large-size (1-4 mm) microplastics (highest abundance of 660 units kg^{-1}) discovered in sediments downstream of storm drainage outlets that enter the Thames River in the United Kingdom, as reported by Horton *et al*., (2017). Since the majority of these microplastics had a sheet-like form, the scientists inferred that they may have come from the adjacent urban area's painted roads. Rainwater eventually washed the microplastics away, causing them to eventually settle in the Thames River sediments (Horton *et al*., 2017). A 2019 study by Wetherbee *et al*. found MPs in the rain that fell over the Rocky Mountains, proving that microplastics in the atmosphere are trapped by raindrops and these contaminates freshwater ecosystems when it rains. Runoffs from rainfall can transport MPs into the aquatic ecosystems by carrying microplastics from various sources such as landfill sites, households, industries and farms into urban wetlands, rivers, and lakes (Wang *et al*., 2021). Aerial transport and deposition is also a significant source of MPs in freshwater in isolated places (Zhang *et al*., 2020). In the French Pyrenees' wet and dry deposition was observed by Allen *et al*., (2019), who discovered that MPs could travel through the atmosphere and affect far and sparsely populated places.

Freshwater sources of MP are more direct and varied than those in the ocean, primarily caused by a deficiency in connectivity between numerous tiny water bodies, which lead to precise localization of pollution features. Since incomplete MPs treatment in freshwater systems can result in MP pollution of the land and ocean, prevention at the source is an efficient strategy to lessen the influence on the freshwater ecosystem. Reducing the use of plastic additives in human activities and sources of sewage discharge, prolonging the lifespan of plastic products, increasing the number of waste treatment facilities (especially in remote regions for managing plastic waste), and enhancing wastewater treatment systems are all practical measures (Siegfried et al., 2017).

2.2.3 Microplastics in Freshwater Ecosystems

Unlike the marine environment, until recently, there has been little research on MPs in freshwater ecosystems. (Wagner *et al*., 2014; Eerkes-Medrano *et al*., 2015). Because of the significant amounts of plastic debris found in lakes and rivers, research on microplastics in freshwater environments is becoming a growing field. The recognition of these elevated levels raises concerns about potential adverse impacts on the ecosystems within these freshwater environments (Mendoza and Balcer 2019). Up until recently, it was unknown how microplastics were distributed in freshwater ecosystems. Only lately have big plastic objects, such as films, lines, and polystyrene, greater than 5 mm to 2 cm, been discovered in rivers (Williams and Simmons, 1996; Moore et al., 2011), estuaries (Sadri &Thompson, 2014) and lakes (Faure et al., 2012). Recent investigations have found microplastics in numerous freshwater ecosystems across different continents. Asia, Europe and North America dominate publications in microplastic research. Microplastics have been discovered in the following regions: Asia, in the Siling Co basin, Tibet (Zhang *et al*., 2016) in Lake Hovsgol, Mongolia (Free *et al*., 2014), Taihi lake, China (Su *et al*., 2016) and the Yangtze river, China (Wang *et al*., 2017); the UK Tamar estuary (Sadri and Thompson, 2014); Europe, in the Italian Lake Garda (Imhof et al., 2013), the German Elbe, Mosel, Neckar, and Rhine rivers (Wagner *et al*., 2014), Lake Geneva (Faure *et al*., 2012) and the Austrian Danube River (Lechner *et al*., 2014), North America, the Great Lakes (Zbyszewski and Corcoran, 2011; Zbyszewski *et al*., 2014; Eriksen *et al*., 2013), the Los Angeles basin (Moore *et al*., 2011), the North Shore Channel of Chicago (Hoellein *et al*., 2014), the St. Lawrence River (Castaneda *et al*., 2014), and the Great Lakes (Zbyszewski and Corcoran, 2011; Zbyszewski *et al*., 2014; Eriksen *et al*., 2013). On the other hand, the African continent has had very few publications up until recently (Nel and Froneman, 2015; Blankson et al., 2022;Chico-Ortiz et al., 2020; Egessa *et al*., 2020). Studies from Li *et al*., 2020 highlights that, areas such as Africa, Middle East, South America and Russia are areas where microplastic monitoring is lacking. To efficiently quantify and resolve the menace of plastic pollution in Africa, studies into microplastic pollution in freshwater ecosystems in Africa must be encouraged. It would be incorrect to suggest that the plastic issue is not widely acknowledged despite the absence of scientific evidence that MPs are present in Africa's freshwaters. The prevalence of MPs in the marine and estuarine environment has, however, been the subject of extensive research and efforts to reduce and eventually ban the use of plastic bags have achieved significant strides in several African nations (Wagner & Lambert, 2018).

Recent monitoring investigations have demonstrated that MPs are ubiquitous in various freshwater matrices, like marine settings. For example, the Rhine River (Germany) has surface water samples with MP concentrations that range from an average of 892,777 particles per km^2 to a peak of 3.9 million particles per km^2 (Mani *et al*., 2015). MPs in beach sediments along the Rhine river ranged from 228 to 3,763 particles kg^{-1} and Main river ranged from and 786 to 1,368 particles kg^{-1} (Klein *et al*., 2018). High surface water concentrations have been observed in the Yangtze River (192-13,617 particles per km^2) near the Three Gorges Dam in China. Microplastic pollution in these regions relate to infrastructure problems with recycling and garbage disposal and a lack of wastewater treatment facilities in smaller cities (Wagner & Lambert, 2018.). Because of their limitations, these investigations might understate the actual MP concentrations.

Studies have shown that only 2% of microplastics in the ocean are caused by marine anthropogenic activity, whereas the other 98% are caused by land-based activity (Boucher and Friot, 2017). Studies by Siegfried *et al*., 2017 reveal that about 70% of the plastics flow from land-based sources into the Mediterranean and the Black Sea due to the low removal rate of plastics, especially microplastics, from wastewater effluent during the wastewater treatment. Additionally, field research in wastewater treatment facilities revealed that river discharge is an effective medium for plastic transport (Reddy and Nair, 2022).

Even in isolated regions, freshwater habitats have been discovered to be contaminated by microplastics; despite the little research on this topic, this shows that microplastics are present in freshwater systems worldwide. Therefore, other ecosystems should be examined to close this knowledge gap about the spread of microplastic pollution in aquatic ecosystems (C. Li *et al.*, 2020). For example, Tanzania, Uganda, and Kenya border the biggest tropical freshwater lake, Lake Victoria, and it is believed that four million people rely solely on the fishing business (Mkumbo and Marshall, 2015). According to Egessa *et al.*, (2020), MPs in Lake Victoria's surface waters ranged from 0.02 pieces per m^3 to 2.19 pieces per m^3, with an average of 0.73 pieces per m^3.

2.2.3.1 Fate of Microplastics in Freshwater Habitat

To a certain degree, MPs' behaviour in natural freshwater environments is determined by their dispersal within the sediment and water column. High-density MPs, such as polyesters (PES) and polyvinyl chloride (PVC), have negative buoyancy, which causes them to sink into the sediment and may make them less prevalent in the water column (Kowalski et al., 2016; Lozoya et al., 2016). Conversely, low-density MPs, such as polystyrene (PS) and polyethylene (PE), are more likely to remain in the water column than high-density MPs because they are positively buoyant. Plastics in aquatic environments are mobile and degrade, producing a mixture of parent materials, broken-up particles in different sizes, and other byproducts of non-polymer breakdown. As a result, biota will be exposed to an intricate blend of plastics and plastic-related chemicals that varies through time and geography.

Degraded microplastics can remain in the sediment or be transported into the ocean by the water column. Those that stay in the sediments serve either as a substrate for the growth of other microorganisms or as a surface for the attachment of certain chemicals. MPs can also be ingested by biota in freshwater, causing harm to these organisms.

2.2.4 Microplastics as Contaminants of Emerging Concern

Microplastics are a legacy of human activity that can be found in both aquatic and terrestrial environments. Eighty percent of plastic waste are generated on land (Andrady, 2011). MPs have become pollutants of concern because, like all contaminants of emerging concern (CEC), there has been an increase in their concentrations, raising environmental problems because of their ubiquity, persistence, as well as possible detrimental effects on aquatic environments (Page *et al.*, n.d.). As a result, microplastic contamination is one of humanity's most significant environmental problems (Lambert and Wagner, 2018). In addition to degrading the aesthetic value of the environment, predominantly aquatic ecosystems, microplastics may be hazardous to people and other animals (von Moos *et al.*, 2012; Wright & Kelly, 2017). Additionally, MPs can introduce chemicals like persistent organic pollutants (POPs) and plastic additives into the aquatic environment (Andrady, 2011; Brennecke *et al.*, 2016).

For many years, little was understood about the scope of dangers brought on by the buildup of MPs in aquatic environments and the underlying mechanisms governing MP movement. Despite recent advancements in our understanding of the potential harm to the world's seas, the consequences of MP on freshwater ecosystems have received less attention (Szymańska & Obolewski, 2020). This has started to change recently, and now both the terrestrial (Lambert *et al.*, 2014 and Rillig, 2019) and freshwater habitats are receiving attention (Eerkes-Medrano & Thompson, 2018; Wagner *et al.*, 2014; Zbyszewski & Corcoran, 2011).

Scientists have recently begun to focus more on the problem of MPs in bodies of water, concerning their concentrations in water and the effects of MP buildup on human health. Many countries such as EU nations, the USA, Canada, and Australia have made significant contributions to the present understanding of the dangers posed by MPs, showing that identifying the mechanisms of MP transformation is a modern and vital area of ecotoxicological research in aquatic ecosystems (Szymańska & Obolewski, 2020).

2.2.5 Impacts of Microplastics

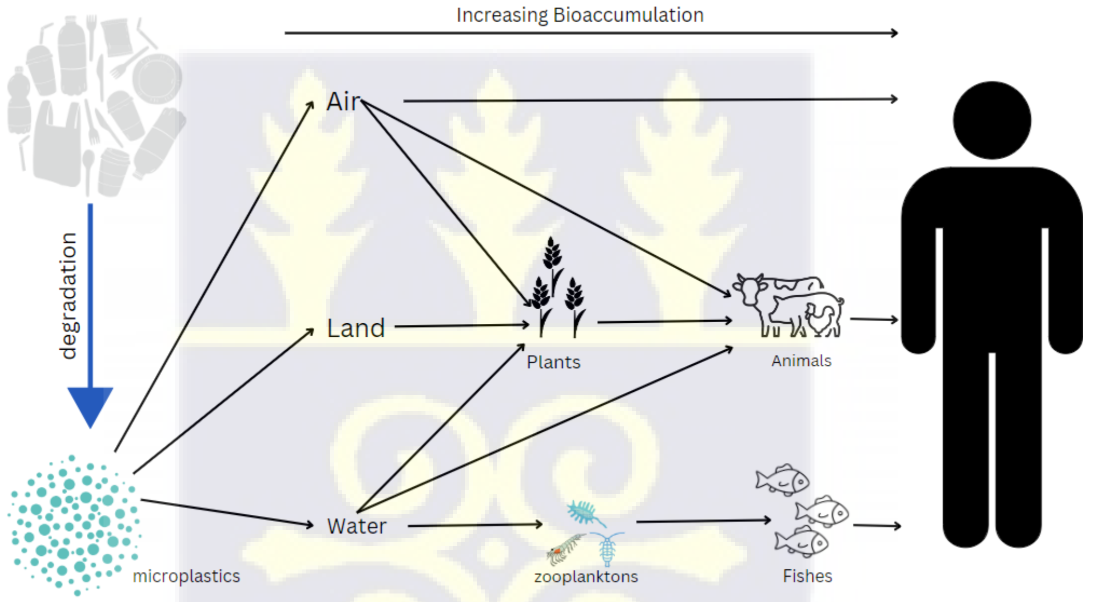


Fig. 2.4: An image of microplastics impact on ecosystems—a comprehensive catalogue of pathway, ecological risks, occurrences and indicators. (Adapted from Okeke et al., 2022)

The pervasiveness and abundance of microplastics cause great concern due to their ecotoxicological properties. Microplastics' bioavailability, which depends on the physicochemical characteristics of MPs, such as particle size and polymer density, determines how they affect organisms (Wu *et al*., 2019; Chen *et al*., 2020; Scherer *et al*., 2017). Furthermore, the location of MPs in the aquatic environment (water surface, water column, and sediment), as well as which organisms are exposed to them, can be determined by the form and density of microplastics because they can vary significantly based on the kind of polymer (De Sá *et al*., 2018). The pathway and uptake of MPs as shown in Fig. 2.4 have primarily been studied in the marine environment. However, there is a need to increase these studies in other aquatic habitats, especially in inland freshwater ecosystems, since freshwater environments are more frequently affected by human activity than marine environments, pollution is a possible risk. in freshwater ecosystems may be more significant (C. Li *et al*., 2020).

Numerous biological and physicochemical processes important to individuals, groups, and ecosystems are impacted by microplastics. A wide range of taxa have shown dose-dependent physiological responses to plastic pollution, including detritivores (Au et al. 2015), algae (Gambardella et al. 2019), deposit feeders (Fueser et al., 2019), suspension feeders (Pedersen et al. 2020), and predators (Kim et al. 2019). Acute endpoints, on the other hand, usually occur at doses that exceed those usually found in nature, and length of time, size of particles, and kinds of exposure influence biological responses, according to systematic reviews of the ecotoxicological effects of virgin plastics on organisms (Foley et al. 2018; Cunningham and Sigwart 2019; Bucci et al. 2020). MPs have been shown to have an impact on plant and animal tissues, cells, and genes (Zhou et al., 2015). Unfortunately, there are very few studies on the toxicology of microplastics and their impact on humans.

2.2.5.1 Microplastic Ingestion

Several studies show that several animal species consume plastics; this data can be separated into deliberate and accidental consumption, with the latter being further classified into inadvertent and nutritional consumption. When an organism intentionally consumes plastic, it does so because it thinks it is a food source. In contrast, incidental consumption occurs when microplastics are ingested together with the organism's regular food source (Yardy *et al*., 2022). Furthermore, a material is considered trophic when it is consumed by another organism that has also consumed plastic (Cole et al., 2011; Cedervall et al., 2012). This allows the MP to migrate between trophic levels.

Fish ingesting MPs has been identified as a globally recognised environmental issue (Wang et al., 2019). Freshwater fish eat MPs when they are deliberately or inadvertently mixed with food (Roch et al., 2020) and take them for food. Fisheries that feed on the sediment bed are subjected to higher concentrations of MP than predatory and omnivorous fish that feed in the water column, as per studies conducted by Jabeen et al. (2017) and Silva et al. (2018).

The bioavailability of MPs to aquatic species, as demonstrated by toxicological research on fish, benthic invertebrates, and zooplankton, is one environmental danger that MPs may present (Li *et al*., 2016; Nel *et al*., 2018). In comparison to other chemical pollutants, MPs are a considerable multiple stressors because of their unique physicochemical characteristics (Potthoff *et al*., 2017), given that plastics contain additives and other chemicals which are toxic to organisms and to humans, additionally MPs are carriers of other pollutants present in the environment.

The breakdown of microplastics in the environment causes the release of chemicals like bisphenol A (BPA). BPA is introduced into both freshwater and marine environments through the leaching of BPA-based products, as well as from discharges in manufacturing facilities, wastewater treatment plants, and landfill sites (Wu and Seebacher, 2020). Bisphenols (BPA) are synthetic organic compounds with a phenolic structure. They find application as additives or building blocks in the manufacturing of polycarbonate plastics and epoxy resins. BPA is recognized for its potential to adversely affect reproduction, development, and overall bodily systems, and is frequently categorized as a substance known to disrupt the endocrine system which causes consequences include immune system and neurological system dysfunction, developmental defects, reproductive interference, and a higher risk of cancer (Ohore and Zhang, 2019). This hazardous xenoestrogen is linked to neoplasms, cardiovascular disorders, and fertility issues (Rochester, 2013).

Microplastics were found in the intestinal tracts of locally caught fish Nile tilapia (*Oreochromis niloticus*) and Nile perch (*Lates niloticus*) in the Mwanza district of Tanzania, south of Lake Victoria (Biginagwa *et al*., 2016). Twenty percent of fish from each species had plastics verified in them, which included polymers such as silicone rubber, PE, Polyurethane (PUR), PS, and PP copolymers. In a separate investigation, the number of microplastics in sediment and *Chironomus spp*. larvae gathered in the Bloukrans River system in the Eastern Cape of South Africa were evaluated; this river flow system suffers temporal fluctuations (Nel *et al*., 2018). The mean concentration of microplastics was 6.3 ±4.3 (n = 21), and 160.1± 139.5 items/kg (n = 23), respectively, for the summer and winter seasons. In the summer, *Chironomus spp*. had about 75% of MPs in the summer and up to 98% in the winter. Blankson *et al*., 2022 recorded MPs in two fish species in the Densu River of Ghana. According to the study, the amount of microplastics found in Bagrid Catfish (*Chrysichthys nigrodigitatus*) (2.88-2.11) and Black-chinned Tilapia (*Sarotherodon melanotheron*) (2.38-1.66) samples was less than that found in *Sardinella maderensis* (40-3.8), *Dentex angolensis* (32-2.7), and *Sardinella aurita* (26-1.6) samples from the nearshore and offshore areas of Coastal Ghana (Adika *et al*., 2020).

Phillips and Bonner, 2015 show that fish from rivers in metropolitan regions had 29.2% more microplastics than fish from rivers in periurban areas. In addition, the abundance of marine life harbouring microplastics was observed in the following regions throughout the western Gulf of Mexico coast: 13.5% fish in bays, 5.9% fish in harbours and 22% fish offshore (Phillips and Bonner, 2015).

Microplastic accumulation in the digestive tract might reduce feeding through false satiation, impacting nutritional gain and energy reserves (Cole *et al*., 2013; Wright *et al*., 2013). For example, researchers found that *B. koreanus* rotifers exposed to 0.05 mm microbeads had stunted growth, decreased fecundity, and shorter life span due to a lack of nutrients (Jeong *et al*., 2016). Ingesting microplastics can also result in impaired cell membrane stability (for example, in the M. edulis digestive tissues), and inflammatory responses may eventually affect energy stores (Browne et al., 2008). According to Rochman et al. (2013), the Japanese medaka fish *Oryzias latipes* experienced early tumour development as a result of ingesting microplastics (size: 0.5 mm), which had sublethal effects on the liver. Growth retardation, hormone disruption, metabolic instability, oxidative stress, immunological and neurotoxic dysfunction, and an accumulation of MPs impacts on behavioural changes related to genotoxicity in fishes (Choi *et al*., 2018).

2.2.5.2 Biomagnification of MPs

MPs are found in edible fish and have been found to reach human systems as a result of biomagnifications (James et al., 2020). It has been demonstrated that many species farther up the food chain display biomagnification (Figure 2.4). MPs were found in planktivorous fish, which biomagnified to greater predatory fish, according to Boerger et al. (2010). In the Mediterranean Sea, biomagnifications have been discovered in albacore, swordfish, and bluefin tuna. (Romeo *et al*., 2015). Nelms *et al*. (2019) reported that MPs were shown to be transmitted trophically from *Scombrus sombrous* to *Halichoerus grypus*. When MPs build up in tissues, the tissues enlarge and become obstructed (Wright *et al.*, 2013; Wang *et al.*, 2016). In vitro experiments reveal that MPs target the crabs' stomachs and gills, altering the way these organs function (Brennecke *et al*., 2016; Karbalaei *et al*., 2018). Fish can expel low-density MPs as pseudofeces even while the majority of MPs stay in the gastrointestinal system (Capone *et al*., 2020; Zhang *et al*., 2021; Prata *et al*., 2020). Humans may experience biomagnifications akin to those of aquatic species. Humans consume fish contaminated with plastic and are exposed to plastic debris.

Oxidative damage, cytotoxicity, and translocation of MPs to other tissues have all been connected to MP exposure (Galloway, 2015; Wright and Kelly, 2017; Anbumani and Kakkar, 2018). MPs may persist in an ecosystem for decades, exposing organisms living there to MPs over an extended period of time. This prolonged exposure can cause immune cell damage, chronic discomfort, swelling, and both cell proliferation and death. (Smith *et al*., 2018)

2.2.5.3 Microplastics as Vector for other Contaminants and Microorganisms

Microplastics have the capacity to either adhere hydrophobic contaminants to their surfaces or internally absorb these contaminants. Such contaminants include heavy metals and persistent organic pollutants (POPs), which they pick up from their surrounding environment (Ashton et al., 2010). For instance, it has been demonstrated that some plastic polymers, including High adsorption capacities for DDTs, polycyclic aromatic hydrocarbons (PAHs), hexachlorocyclohexanes, and chlorinated benzenes are exhibited by polyvinyl chloride, polyethylene, polypropylene, and polystyrene (Lee *et al.*, 2014). Furthermore, it has been demonstrated that persistent organic pollutants such polychlorinated biphenyls (PCBs) and organo-halogenated pesticides are present in plastic pellets that have been found stranded on beaches all over the world (Heskett *et al.*, 2012). The overall concentration of PAHs on plastic pieces found on beaches was as high as 45.0 ng/g, according to Hirai *et al.*, (2011). In contrast, the concentrations of pesticides with organochloride and polychlorinated biphenyls were determined to be 200 ng/g and 450 ng/g, respectively. (Mizukawa *et al.*, 2013).

MP has been shown to contain nonylphenol and bisphenol A (Campanale *et al.*, 2020). A number of plastic additives, including some well-known endocrine disrupting chemicals (EDCs), were found in MP (e.g., phthalates) (Fries *et al.*, 2012; Wagner and Oehlmann, 2009 & 2011). The chemical burden of freshwater MPs must be researched because the range of contaminants in marine and freshwater systems differs. MPs might serve as a vector for dispersing toxins from the environment into the biota. Despite conflicting results from modelling studies (Teuten *et al.*, 2007; Gouin *et al.*, 2011), a recent experimental investigation shows that fish exposed to MPs bioaccumulate these substances and exhibit adverse effects (glycogen depletion and histopathological alterations) (Bhuyan, 2022).

In addition, MPs provide surfaces for the attachment of microorganisms and hydrophobic inorganic pollutants, which may be harmful to the body when ingested (Wang *et al*., 2016; Manzoor *et al*., 2020). Physical properties such as hydrophobicity of microplastics enable them to develop microbial colonies on their exterior in aquatic environments (Zettler *et al*., 2013). Pathogens and other microbes could attach themselves to microplastics and form biofilms. In the North Atlantic, a highly varied microbial population known as a "plastisphere" was found to be clinging to plastic marine waste, according to Zettler *et al*. (2013). Hydrocarbon-degrading bacteria that make up a number of the components of the plastisphere can affect the fragmentation and breakdown of plastic waste. In addition, some *Vibrio* species have been discovered in MPs (Harrison *et al*., 2012; Carson *et al*., 2013). Microplastics have the potential to act as a conduit for some disease-causing organisms. (Yuan *et al*., 2020). These microbial colonies are distinct forms in the aquatic ecosystems and may contain harmful bacteria, including the gram-negative *Vibrio*, which causes diseases (Leighton *et al*., 2023).

According to earlier research by Rodrigues *et al*., 2019, bacteria, viruses, or other contaminants (such as heavy metals, organic pollutants) adhere to the surfaces of MPs, hence can gain entrance to the food web by ingestion of MPs by smaller organisms. Under laboratory conditions, MP exposure negatively impacted aquatic animals' nutrition, metabolism, behaviour, and reproduction (Cole *et al*., 2015; Chen *et al*., 2017).

Recent studies have demonstrated that contaminants like polybrominated diphenyl ethers (PBDEs), perfluorochemicals, other pharmaceuticals and personal care products (PPCPs) can all be absorbed onto microplastics (Wardrop *et al*., 2016). Microplastic-adsorbed contaminants that are released into the environment can have a variety of toxicological impacts on organisms. The multiple effects of MPs and other contaminants cause multiple stress in the freshwater ecosystem. The concept of multi-stressors highlights the need to understand the complex interactions and synergistic effects that can occur when multiple stress factors are present simultaneously (Lima *et al.*, 2023). Toxicological studies are required to determine the multiple effects of microplastics with a variety of other common contaminants because there are multiple stressors at play with varying impacts on the ecosystem and a single toxicity of just one contaminant will not be a true reflection of the actual risks at play.

There is a chance that toxins like Diethylhexyl Phthalate and other toxins from MPs will lead to malignancies, birth deformities, and immune system problems (Auta *et al.*, 2017; Sutton *et al.*, 2016). However, the intake of microplastics and their biological effects on marine species infected with them are still not fully understood (Shahul Hamid *et al.*, 2018).

Enhancing the life cycle of plastic products, education on plastic use and its impacts and implementing effective waste management strategies can significantly reduce the amount of plastic waste introduced into the environment, allowing the aquatic ecosystem to recover. Pahl and Wyles (2017) state that the human dimension (behavioural and attitudinal science), in conjunction with our knowledge gained from natural sciences, will be vital in tackling the challenges of microplastics waste in the environment.

2.2.5.4 Other Impacts

In addition to the direct effects on living organisms and the possibility of trophic transfer, there is a chance for broader environmental consequences, such as potential impacts on biological communities and ecosystems. Changes in biota behaviour or organization (Chen *et al*., 2011), modifications in the bioturbation and oxygenation of sediments (Wright *et al*., 2013b), and effects on carbon flux are a few examples of issues that fall under the category of broader environmental consequences (Chen *et al*., 2011).

2.3 Occurrence (Abundance and Spatial and Temporal Distribution)

In recent times the study into the occurrence of microplastics in freshwater environments has increased, with most of the study taking place in Europe, Asia and the Americas (Moore *et al*., 2011; Faure *et al*., 2012; Wagner *et al*., 2014; Wang *et al*., 2017). These studies typically consider the abundance, spatial and temporal distribution and the effects of hydrology on occurrence. Data on the occurrence of MPs in freshwater ecosystems enables effective remedies to be developed for their removal and also measures taken to reduce the number of plastics entering these ecosystems. Furthermore, worldwide knowledge of morphology and microplastic types also helps assess environmental risks (Wagner *et al*., 2014).

Freshwater habitats have very limited if any, available data on MPs, especially in Africa, including in Ghana. This lack of information makes using scientific methods to evaluate freshwater MP's environmental danger challenging. Such an evaluation is necessary to promote public and political discourse on the matter at the national and global levels, the conclusion of which will ultimately determine mitigation measures. For example, MP might be used as a descriptor of environmental status (Wagner *et al*., 2014)

Environmental challenges and anthropogenic activities (Sarafraz *et al*., 2016) are the main driving factors of microplastic quantity and distribution (Kim *et al*., 2015;

Veerasingam *et al*., 2016; Imhof *et al*., 2013). However, the spatial distribution of MPs may be influenced more by environmental and physical than anthropogenic variables (Herrera *et al*., 2017; Zhang *et al*., 2016). The distribution of microplastic is controlled by a variety of environmental factors, such as wind directions (Kukulka *et al*., 2012; Thiel *et al*., 2013; Sadri and Thompson, 2014; Liubartseva *et al*., 2016), wave currents (Kim *et al*., 2015), tides, cyclone and river hydrodynamics. Dekiff *et al*. observed that wind and water currents were responsible for the spatial distribution of plastic debris in sediments. Where these environmental conditions are more pronounced, there will be a greater microplastic concentration.

2.3.1 Abundance

Abundance refers to the quantity or number of microplastic particles or fragments present within a specific sample or area (Rivers *et al*., 2019). It is a measure of how many individual microplastic particles are found in a given environment, such as water, sediment, soil, or organisms. Abundance data are crucial in understanding the extent of microplastic contamination in an ecosystem and assessing its potential impact on the environment and organisms (Lusher 2015). Researchers often quantify microplastic abundance to track trends, assess pollution levels, and evaluate the effectiveness of mitigation strategies.

Recent monitoring efforts have demonstrated that MPs are ubiquitous in various freshwater matrices, like marine settings. Worldwide, freshwater systems, including those in North America, Asia, Europe and Africa, have been found to contain large amounts of MPs. For example, Mani *et al*., 2015 show that the Rhine River (Germany) has surface water samples with MP concentrations that range from 892,777 particles

Rivers in Germany, respectively, the number of particles in river beach sediments ranged from 228 to 3,763 and 786 to 1,368 particles per kg (Klein *et al*., 2015). Similarly, MP particles have been detected in surface water from the Laurentian Great Lakes in both Canada (Zbyszewski and Corcoran, 2011) and the United States (Eriksen et al., 2013). Approximately 99.9% of the microbeads found in the North American study were spherical, less than 2 mm in diameter, and composed of polyethylene (PE) (Free et al., 2014). In the sediments of the Thames River, Horton *et al*. (2017) examined the origin and prevalence of microplastics. The authors found that at a drainage outfall that receives urban runoff contained paint fragments from road markings, which contributed to the notably higher concentration of plastic particles.

Plastic was prevalent in the water column, ranging from 56 pieces/ m^3 to 288 pieces/m^3 according to a study of the Netravathi River in southwest India that looked at macro and microplastics contamination in sediment and water samples (Amrutha and Warrier, 2020). The amount of plastic in sediment increased downstream of towns with high population density. Plastic density was observed to vary as follows: upstream>midstream<downstream. Similar to the sediment data, the lowest values were found in areas with less anthropogenic pressure, ranging from 253 pieces kg^{-1} to 9.4 pieces kg^{-1}. Interestingly, the area with the worst water contamination had the least sediment pollution, only 17.6 pieces kg^{-1}. This anomaly can be explained by the turbulent currents of wind, rain, and monsoon resuspending MPs from sediment into the water column (Amrutha and Warrier, 2020).

Furthermore, Zhang *et al*. 2016 hypothesized that riverine input might be responsible for the high amounts of microplastic (563-1219 items m^{-2}) discovered in the sediments of distant lakes on the Tibet Plateau with little human activity (Zhang *et al*., 2016). Since tributary inputs play a crucial role in the increased concentrations of microplastic in the confluence places of the Pearl River in Guangzhou, environmental factors such as these also impact the abundance of microplastics in urban areas (Lin *et al.*, 2018).

Lahens *et al.*, in 2018, investigated the microplastics in the Saigon River in Vietnam and found that the lowest size categories (50-250 µm and 0.5-50 103 μm^2) accounted for half of the MPs documented; microplastics were also classified as fibres or fragments. Although both fibres and fragments were the least upstream and increased downstream, the difference was less than expected, given the difference in population between the sites. Most of these MP were fibres, up to 519,000 fibres m^{-3}, as opposed to a maximum of 23 pieces m^{-3} (Lahens *et al.*, 2018).

The Three Gorges Reservoir in China was the subject of an investigation by Zhang *et al.*, 2015, who discovered the greatest level of microplastic abundance ever documented in the literature: 136,175±106 items/km^2. According to the authors, damming may contribute to high microplastic accumulation, and reservoirs may operate as potential microplastic hotspots (Zhang *et al.*, 2015). In Taihu Lake, the third-largest freshwater lake in China and heavily influenced by humans, Su *et al*. 2016 reported microplastic pollution. Samples of sediment, surface water and Asian clams all contained microplastics. Wuhan, the largest city in Central China, has researched microplastic pollution in inland freshwaters (Wang *et al.*, 2016). Surface water contained concentrations of microplastics ranging from 1,660-639.1 to 8,925-1,591 items/m^3, and the abundance of microplastics was adversely linked with distance from the city centre. Results showed that there were large numbers of microplastics in these areas where rivers and the sea meet, indicating that rivers are significant suppliers of microplastics for the marine environment.

Sarkar *et al*., 2019 conducted a study along the Ganga River in India. They found that microplastic were discovered in all sediment samples with abundance (99.27-409.86 items/kg). According to Fourier transform infra-red (FTIR) analysis, polyethene terephthalate (39%) and polyethylene (30%) were the two most significant contributors to plastic debris in the sediments. Furthermore, a statistical investigation revealed significant relationship between the quantity of microplastics and the pollution characteristics of sediment and water, specifically BOD and accessible phosphate, respectively (Sarkar *et al*., 2019).

In Africa, the influx of raw sewage and the disposal of household and industrial garbage pose a threat to Lake Victoria, which Kenya, Uganda, and Tanzania surround. In Northern Lake Victoria's surface waters, MPs were surveyed, and it was discovered that most of them appeared to be secondary MPs produced from larger plastic debris, possibly due to ineffective waste management (Egessa *et al*., 2020). In Ghana, studies on the Densu River by Blankson *et al*., 2022, reveals that Weija had 16 microplastic particles retrieved for every 40 g of sediment compared to the Densu Delta's 15 microplastic particles. Similarly, five microplastic particles per 60 ml of water were found at the Densu Delta as opposed to nine microplastic particles in the Weija Dam.

Since different sampling techniques and quantification units were used in the various freshwater investigations, it is challenging to compare the MP concentrations reported in those studies (Horton *et al*., 2017). In addition, studies differ significantly in the types of MP (such as size, shape, density, and composition) that are recorded, as well as the abiotic factors (such as weather, season, and equipment employed) that may have an impact on MP distribution, which further complicates the problem of comparability (Lattin *et al*., 2004; Hidalgo-ruz *et al*., 2012).

In the Danube River, pellets, fragments, and spherules MPs from industries made up 79% of the plastics collected over a two-year assessment of drift samples (2010 and 2012) (Lechner *et al*., 2014). This was due to activities related to plastic production within the river basin (Lechner and Ramler, 2015). Spherules measuring 300-100 µm in size were the most prevalent particle type. Mani *et al*., 2015 reported 60% of the total sampled microplastics in some section of the Rhine River. Fragments were the second most frequent particle type in the Rhine investigation. The study's authors highlighted a large number of plastic manufacturers and processing facilities some sample sites with high microplastic contents predominately made up of spherules (Mani *et al*., 2015).

Compared to the Rhine (Mani *et al*., 2015) and Danube Rivers (Lechner *et al*., 2014), where scientists found a connection between high levels of primary microplastics and industrial activity near the study sites for sampling, (Lechner and Ramler, 2015), other surface waters sampled showed same trend of high MPs concentrations in industrial areas along the rivers, e.g. the Yangtze and Hanjiang Rivers in China (Su *et al*., 2016; Wang *et al*., 2017): the tributaries of the Great Lakes in Canada (Fischer *et al*., 2016; Anderson *et al*., 2018) and the Seine River in France (Dris *et al*., 2015; Ballent *et al*., 2016)

In sediment sample reports, fibres have also been identified as the predominant particle type (e.g., Ballent *et al*., 2016; Su *et al*., 2016). Based on the chemical makeup of the fibres, researchers discuss possible origins of these MPs, e.g., the main component of some domestic and agricultural materials are polypropylene (PP). Similarly, polyethylene terephthalate (PET) is also made into fibre to produce textiles (Dris *et al*., 2017; Wang *et al*., 2017). Furthermore, PE, PP, and PS particles collectively accounted for >75% of all polymer types detected in the sediments in a study of the Rhine and

Main Rivers in Germany, indicating their extensive use in agriculture, food packing, and industrial pipelines (Klein *et al.*, 2015).

Eo *et al*. (2019) observed that of the microplastics in the water of the Nakdong River, polyester made up 23.1% and polypropylene 41.8%. In contrast, polypropylene and polyethylene made up around 50% of the sediment. Also, 74% of the water and 81% of the sediment contained microplastics less than 300 µm, with the distribution peaking in the 50–150 µm size range.

White, translucent, blue, and black are the predominant colours of MPs in freshwater habitats. The majority of the transparent and white MPs were found in sewage treatment facilities (Long *et al*., 2019; Yuan *et al*., 2020). The number of transparent MPs increased for two reasons; i) there are more transparent MPs present, and ii) coloured MPs have been exposed to the weather and environmental deterioration for a considerable amount of time (Pan et al., 2020). According to Li *et al*. (2018), 59.6% of white MPs were in some Chinese wastewater treatment facilities, while the percentages of transparent and black MPs in the Ofanto River were 56% and 35%, respectively (Campanale *et al*., 2020). In water and sediments, transparent MPs were prevalent.

2.3.2 Spatial and Temporal Distribution

Spatial and temporal distribution pertains to how objects, features, or phenomena in this case MPs are organized or patterned in both geographical space and over time. In the context of MPs, understanding their spatial and temporal distribution offers valuable insights into the arrangement and attributes of MPs within the Odaw River, as well as the seasonal trends associated with their presence.

Spatial and temporal factors play a major role in the distribution of microplastics in freshwater ecosystems especially in rivers. Seasons and hydrological conditions may influence abundances of MPs at different sections of a river. Despite carrying more particles per unit of time, rivers with higher flow patterns typically create lower concentrations than those with lower flows (Watkins *et al*. 2019). Extreme rainstorms, seasonal variations in flow regimes (such as flooding or drought), and human-induced controls on streams (such as spillway gates and dams) can all affect the concentration and transit of microplastics (D'Avignon *et al.*, 2022). Spatial and temporal fluctuations in abundance of MPs require frequent and larger monitoring scale to highlight representative concentrations of MPs in aquatic environments.

MPs are more prevalent during the wet season than during the dry season. For example, Wu *et al*., 2020 reported that in the wet season, the quantity of microplastics in the Maozhou River in Hong Kong in water and sediments recorded MPs abundance range from 4.0 ± 1.0 to 25.5 ± 3.5 items per liter and 35 ± 15 to 560 ± 70 items per kilogram respectively. there was a significant difference in both wet and dry seasons (water: p value < 0.05; sediment: p value < 0.05) where the range was 3.5 ± 1.0 to 10.5 ± 2.5 items per liter of water and 25 ± 5 to 360 ± 90 items per kilogram of sediment. The increased rainfall during the wet season, accounts for approximately 80% of the annual precipitation in the Maozhou watershed (Liao et al., 2019), and this may contribute to higher river flow (Zhao et al., 2019) and lead to a dilution of microplastics concentration in the river (Yan et al., 2019). Rodrigues *et al*., 2018, in their study on the Antua River in Portugal, also found that their results were following the general assumption that MPs abundance usually increases in the wet season. Their results showed that MPs presence exhibited higher levels during the wet season compared to the dry season, ranging from 5 to 8.3 mg per m^3 or 58–193 items per m^3 in March, and from 5.8–51.7 mg per m^3 or 71–1265 items per m^3 during the wet season. This disparity was attributed to widespread improper waste disposal on a large scale, directly linked to the elevated population density and proximity to urban zones.

Nel *et al*. (2018) evaluated the dynamics of microplastic pollution in an urban river sediment subject to temporal variations in the river flow. They discovered that the amount of microplastic in winter was roughly 25 times higher than in summer, most likely due to increased sedimentation brought on by decreased river flows in the winter.

The presence and quantity of microplastics along a river can be affected by their specific location, which is determined by a combination of hydrological conditions and other relevant factors. For instance, results from Vermaire *et al*., (2017) show that MPs concentrations in surface waters and sediments of the Ottawa River in Canada were significantly higher downstream of the wastewater treatment plant than upstream of the effluent output, (Vermaire *et al*., 2017).

MPs from sediments in the St. Lawrence River investigated by Crew *et al*., 2020 were among the highest levels ever discovered (in the top 25%) in freshwater and marine systems around the globe. The average amount of microplastics found in all sediment sampling locations was 832±150 plastics per kg dry weight with a range of 65 to 7562 plastics per kg dry weight. Several environmental factors, such as land utilization and the attributes of sediment particles, played a substantial role in determining the levels of microplastics in the sediment (Crew et al., 2020). The differences in the makeup of microplastics within the sediment were, to some extent, associated with particle properties, proximity to urban land areas (point sources), and ecological filters (like sediment composition, organic and inorganic carbon percentages, and distance from the shoreline).

Stanton *et al*., 2020 investigated spatiotemporal changes in microplastic concentrations across a number of freshwater ecosystems in the United Kingdom (UK) where MPs were detected in low amounts at all sites studied, including upstream of metropolitan areas and rivers that do not receive wastewater treatment plant effluent (max 0.4 particles L^{-1}). Microplastic studies that overlook temporal variability run the risk of inflating the prevalence of microplastics, as evidenced by the up to 8 orders of magnitude fluctuation in the extrapolated microplastic abundances at each location (Stanton *et al.*, 2020). These results suggest that seasonal variation must be taken into account in order to estimate microplastic transmission. Ignoring these parameters could lead to an overestimation or underestimation of the annual burden of microplastics.

2.3.3 Ecological Risk Assessment

Ecological risk assessment is a process used to evaluate and understand the potential adverse effects of environmental stressors, such as chemicals, contaminants, or physical changes, on ecosystems and the organisms within them. It aims to determine the likelihood and severity of these effects and to inform decision-making and environmental management (Gouin *et al*., 2019). In the 1980s, risk assessment methodology began to take shape (Qiu *et al*., 2023). It became widely employed in various industries, including engineering safety, management of toxic chemicals, environmental protection, and the prevention and control of disastrous accidents. Risk assessment describes and calculates the likelihood that undesirable or undesired occurrences may occur (He & Huang, 2019). Understanding the ecological risk of chemicals is essential for developing effective environmental management strategies for contaminants (Lei *et al*. 2008).

Regulators, the scientific community, and the general public are becoming increasingly concerned about the ecological damage posed by microplastics (Gouin *et al*., 2019). This highlights the necessity of improving our knowledge of microplastics' ecological impacts and fate in the aquatic environment. Unfortunately, there is insufficient scientific information to enable evidence-based decision-making regarding ecological exposure to, impacts of, and risks presented by microplastics. Understanding the spectrum of possible exposures, their temporal and spatial variability, and the likely ecological receptors is crucial to assess the likelihood of negative impacts (Syberg *et al*., 2015).

The research on microplastics' adverse effects as a new pollutant primarily focuses on how they affect living things. Nevertheless, it is still rare to quantify the risk of microplastics in a place (Li *et al*., 2021). An ecological risk assessment of microplastics can be analysed qualitatively and quantitatively using data on the source, sink, fate, and abundance of microplastics in different habitats, migration routes, the combined toxicity of persistent organic pollutants, the transport of harmful microbes attached to microplastics, and ecotoxicological effects, among other things. For microplastics, evaluating ecological risks is very difficult. There are still issues with microplastic risk assessment, such as a lack of standardized sampling/quantification techniques and clearly defined environmentally relevant microplastic concentrations (Peng *et al*., 2018).

The widespread perception of microplastic as an environmental problem is that it has unique qualities, one of which is its complexity (Rochman, 2019; Kooi, 2019). The persistence profiles, fate processes, and impact of microplastic particles have received the majority of attention from researchers examining microplastics. Therefore, a more accurate picture of the risk posed by microplastics can be obtained by considering their complexity and that of natural particles (Koelmans *et al.*, 2022).

Frameworks for evaluating the risks of microplastic particles have been established by several scientists (Lithner *et al.*, 2011; Koelmans *et al.*, 2017; Besseling *et al.*, 2019; Gouin *et al.*, 2019). Common methods for assessing the ecological risk of microplastics (MPs) mainly involve the utilization of the pollution load index (PLI) and pollution hazard index (PHI). These indices are applied to evaluate the levels of MP pollution across various regions, taking into account both MP abundance and the chemical toxicity of the polymer (Peng et al., 2018; Kabir et al., 2021). The formula used to assess the risk index for polymers in this study was developed by Lithner *et al.*, 2011

$$H = \sum Pn \times Sn \qquad (1)$$

Where Sn is the plastic polymer's hazard score, Pn is the ratio of the polymer concentration of different kinds of microplastics to the total concentration of microplastics, and H is the polymer's risk index. For the various plastic polymers that are accessible, there are distinct hazard scores (Sn). As an illustration, consider the Sn values of 1, 11, 30, and 5001 for polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC) (Lithner et al., 2011).

Along with MP polymers, MP concentration is a crucial indicator for assessing the danger associated with MP. In order to evaluate the level of pollution the Pollution Load Index (PLI), which is connected to MP concentration, must be investigated (Tomlinson *et al.*, 1980). The link between PLI and MP concentration (Ci) at each sampling location guided the setup of the PLI model, which may be summed up as follows:

$$PLI = \sqrt{C_i / C_{oi}} \qquad (2)$$

$$\text{PLIzone} = \sqrt[n]{\text{PLI}_1\text{PLI}_2\ldots\text{PLI}_n} \qquad (3)$$

where the lowest MP concentration at each sampling location is denoted by Coi. PLI values are calculated using the Coi (0.01 particles/L) as the minimum average concentration, in accordance with studies conducted by Isobe et al. (2014) and Xu et al. (2018). The risk category is provided in (Liu et al., 2022). It corresponds to the hazard scores and PLI.

According to a study by J. Li *et al.*, 2021, a risk assessment of MPs in the Chishui River in the Renhuai Basin showed that the risk of microplastics in the basin is 111.79. Based on studies, the risk level of microplastics is categorized into four groups, I, II, III, and IV. The risk of microplastic pollution increases as the level rises (Li *et al.*, 2020). Renhuai City has a class III level of pollution for microplastics, which is a secondary risk area (J. Li et al., 2021). Other studies, such as Peng *et al*., 2018 found a highly toxic chemical phenoxy resin in microplastics in river sediments in Shanghai, China. Although direct toxicity data on phenoxy resin is lacking, its main ingredient, bisphenol A, is toxic to mammals and aquatic organisms (Ohore and Zhang, 2019).

A study by Y. Li *et al.*, 2021 on aquaculture systems from south China showed that the types of MPs in sediment and that in surface water showed potential risk due to the chemical toxicity of several discovered polymers, such as PMMA and Polyvinyl chloride (PVC). It has been demonstrated that vinyl chloride, the primary monomer of PVC, increases the risk of cardiovascular disease and causes hepatic angiosarcoma (Huang *et al.*, 2011; Sirit et al., 2008). In addition, animals exposed to vinyl chloride also displayed renal parenchymal lesions and oedema (Viola, 1971).

2.4 Interaction of MPs with other Biotic and Abiotic Factors

In general, plastics, particularly MPs, can serve as factitious surfaces for microbial colonization and adsorption of toxic compounds (Rummel *et al*., 2017). The interaction of MPs with toxic compounds and microorganisms may intensify their harmful effects on living things. Physical, chemical, and biological factors can all impact how MPs interact with the environment (Kowalski *et al*., 2016; Lu *et al*., 2019).

MPs are known to interact with some toxic compounds that have been linked to mutagenic, teratogenic, and carcinogenic consequences (Campanale *et al*., 2020), this behaviour of microplastics interacting with these compounds can pose environmental challenges. Some of these chemicals reported include persistent organic pollutants (POPs) such as polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and heavy metals such as Arsenic (As), manganese (Mn), aluminium (Al), lead (Pb), copper (Cu), silver (Ag), zinc (Zn) etc. (Verla *et al*., 2019). Heavy metals have been discovered adherent to MPs from the North Atlantic subtropical gyre also known as the Great Pacific Garbage Patch (Prunier *et al*., 2019), beaches in southwest England (Massos and Turner, 2017), western Europe (Turner *et al*., 2019) and Africa (Baguma *et al*., 2022; Enyoh *et al*., 2022).

Microorganisms are pivotal in the natural world, serving as nature's ultimate recyclers (Qiu *et al*., 2022). They break down organic matter, releasing essential nutrients, crucial for nutrient cycling and ecological balance. However, with the introduction of MPs in the ecosystem, the interaction between MPs and microbes cannot be disregarded and these interactions intensify with the increasing discharge of plastics. However, the complexity of the interaction between plastics and microbes depends on the diversity of MPs and the quantity of various bacteria (Qiu *et al*., 2022). MPs can also serve as an emerging ecological niche for microorganisms where they create microbial biofilms known as plastispheres (Yang *et al*., 2020). MPs can support microbial colonization and potentially act as carbon sources for microbial growth in the plastisphere (Mammo *et al*., 2020).

2.4.1 Abiotic Interactions (chemical interactions)

2.4.1.1 Organic compounds

The use of large amounts of organic-based chemicals (Foley et al., 2018) by many industries (e.g., printing, textile, paint, paper and pulp, pesticide, petroleum, pharmaceutics, etc.) is causing an increasing number of hazardous organic pollutants, such as antibiotics, polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls phthalates (PCBs), and phenols, to be released into the water and soil environment (Xiang *et al*., 2022).

Organic pollutants' high toxicity and poor biodegradability cause a variety of environmental issues, including harm to aquatic life (Foley *et al*., 2018), obstruction of sewage treatment facilities (Turan *et al.*, 2021), and a spike in biochemical oxygen (Kataoka et al., 2019). These issues could pose severe risks to human health and the ecosystem (Wang *et al*., 2014). Recent investigations suggested that organic contaminants from soil and water could be attracted to and concentrated by microplastics. Consequently, the concentrations of organic pollutants in microplastics are hundreds or thousands of times higher than in the air (Hirai *et al*., 2011; Zhao *et al*., 2020).

Guilhermino *et al*. investigated the impact of antibiotics (such as florfenicol) and microplastics on the bivalve (such as *Corbicula fluminea*) (Guilhermino *et al*., 2018).

They discovered that *Corbicula fluminea* would acquire or retain antibacterial florfenicol and microplastics after ingesting them from the aquatic environment. The findings showed that in terms of neurotoxicity and oxidative damage for *Corbicula fluminea*, the toxicity resulting from the combination of microplastics and the antibacterial florfenicol was greater than the individual toxicity (Guilhermino *et al*., 2018)

2.4.1.2 Inorganic Compounds

Heavy metals

Since the beginning of the industrial revolution, the expansion of industrial activity has benefited humanity. However, these industrial activities also have detrimentally impacted the environment. For instance, several enterprises have improperly released wastewater containing heavy metals into the aquatic environment, including those in the mining, refining, electroplating, equipment, and paper industries (Zheng *et al*., 2020). Globally, the release of heavy metals into the environment is accelerating (Khalid et al., 2021). Waste water from various industries is released into the environment, mainly into the local water bodies (rivers and streams). These are the principal sources of some heavy metals such as Cr, As, Cu, Al, and Fe (Duncan *et al*., 2018). These effluents are discharged into nearby rivers in low- and middle-income nations without any waste removal procedures in place (Aqeel et al., 2021; Khalid et al., 2021). Furthermore, roadside soils frequently get enriched in certain heavy metals, such as Pb, Cd, Ni, Zn, and Fe, which are regularly released by automobile exhaust (Khalid et al., 2021). These metals end up in adjacent aquatic environments after a downpour.

This has contributed to the rise in heavy metal pollution during the last few decades. The entire food chain experiences bioaccumulation due to the low degradability, high pathogenicity, and widespread dispersion of heavy metals in water (Xiang *et al*., 2022). Many recent studies have looked at the environmental toxicological interaction between heavy metals and microplastics (Ekett *et al*. 2018; Zhou *et al*., 2019; Lipp *et al*., 2020; Wang *et al*., 2020).

According to Ekett *et al*. (2018), sediments serve as reservoirs for both non-toxic and potentially hazardous metal(loid)s as well as the ultimate resting places for microplastics (Peng *et al*., 2020; Zhang *et al*., 2020b). Studies have demonstrated a close correlation between increased metal concentrations in MPs and metal concentrations in the sediment and water column nearby (Ashton et al., 2010). The oxides of several elements, including Al, Ca, Mg, K, Si, Na, and Fe, greatly influence sediments' chemistry (Lipp *et al*., 2020). Additionally, the presence of organic materials in the coastal sediment, such as coal, oil, dead plants and animals, and organic waste, contributes to the enrichment of biophile metals, including B, Ca, Mg, K, Na, V, Fe and Cu (Adegoke *et al*., 2014).

While metal ions are necessary micronutrients, they can also be among the most dangerous environmental pollutants when present in excess (Johnson et al., 2017). The exact nature and mechanisms of the interaction between MPs (meso/microplastics) and heavy metals are still unknown, but reports of coexisting metals adsorbed on plastic particles in environmental settings (Kutralam-Muniasamy et al., 2020) and sorption capacities for metals observed in laboratory settings (more than 40% of some dissolved metals are adsorbed in current experiments; Holmes et al., 2012) raise concerns about the likely ecological implications of MP-metal interaction (Naqash *et al*., 2020) and alteration of the cycling of elements.

Furthermore, Wang *et al*. examined how the microplastics polylactic acid and polyethene affected the arbuscular mycorrhizal fungus community and plant performance in agricultural soil (Wang *et al*., 2020). They discovered that Polyamides (PA) increased Cd bioavailability more than polyethylene (PE), although the plant's Cd level remained unchanged (Wang *et al*., 2020). They further proposed that the cohabitation of microplastics and Cd can lead to changes in root symbiosis and plant performance, which is detrimental to soil biodiversity and agro-ecosystems (Wang *et al*., 2020).

According to Zhou *et al*., 2019, MP particles in the soil environment in suburban China contained variable quantities of heavy metals, including Cd, Cr, Pb, Ag, Cu, Sb, Hg, Fe, and Mn. The high association between the number of heavy metals in soils and MP particle content suggests that the number of heavy metals in MPs may be closely correlated with the level of heavy metal pollution in the soil environment. Additionally, there was a significant link between the amount of MP particles and the metal concentration, indicating that MP abundance affects the heavy metal content. These findings suggest that MPs in soil environments may act as vectors for transferring heavy metals (Zhou *et al*., 2019).

Kim *et al*. investigated the effects of two types of microplastics—one lacking a carboxyl group (PS) and the other coated with a carboxyl group (PS-COOH)—on the toxicity of nickel (Ni) in the aquatic insect *Daphnia magna* and the toxicity of a mixture of PS/PS-COOH and Ni on the water flea *D. magna* (Kim *et al*., 2017). According to the acute toxicity test results, the combined toxicity of PS and Ni on *D. magna* was less than the individual toxicity of Ni. However, the combined toxicity of PS-COOH and Ni on *D. magna* was more than the individual toxicity of Ni (Kim *et al*., 2017). This implies that the combined effects of these two MPs polymers with or without carboxyl and Ni had a higher effect on the organism as compared to the effects of the only Ni. This goes to prove that heavy metal interactions with MPs have adverse effects on microorganisms.

In a study by Fred-Ahmadu *et al*., 2022 of microplastics and mesoplastics throughout the Nigerian Gulf of Guinea coast showed that a total of 3680 particles were identified and described from MPs that were discovered at various coastal areas along the drift and high waterlines of the coast of Nigeria. According to the study, shoreline MPs were mainly made of polyethylene (PE), polypropylene (PP), and polystyrene (PS), while plastics recovered from lagoon areas were primarily made of polyethylene terephthalate (PET), polystyrene (PS), and polyurethane (PU). Compared to hard plastic (PE, PP, PET) samples, metal concentrations were greater in foam plastic (PS, PU, PEVA) samples. High quantities of Al, Fe, Mn, and Zn were discovered in every sample, pointing to environmental sorption and potential additive sources. MPs in foam had a stronger affinity for metals.

According to Patterson *et al*., 2020 microplastics in an Indian coral reef pollution indices such as enrichment and contamination factors show that Zn, Hg, Cd, P, and Ni moderately contaminated sediments. The fact that there is more heavy metal associated with MPs than in sediments suggests that either MPs are a source of metal pollution or that metals from sediment preferentially adhere to MPs. Scan electron microscope analysis shows that many MPs' surfaces have cracks, protrusions, and deposits, indicating partial degradation and these surfaces makes it easier for heavy metals to adhere to MPs (Patterson *et al*., 2020).

2.4.1.3 Factors Affecting Adsorption of Heavy Metals

The sorption of a compound is defined as the chemical transitioning from a fluid phase, like air or water, to a solid phase, exemplified by plastic debris or dissolved organic matter (DOM). Absorption and adsorption are two different processes that are related to this phrase. The chemical contact between substances and a sorbent through comparatively mild van-der-Waals forces, in which molecules pass through and become entrenched in the matrix sorbent, is called absorption (Menéndez-Pedriza & Jaumot, 2020). In contrast, the term "adsorption" refers to a number of forces, including van der Waals, ionic, steric, or covalent interactions. (Menéndez-Pedriza & Jaumot, 2020).

Understanding a complex array of synergistic and antagonistic processes in the solution and at the interface between the polymer and the aqueous phase is necessary to mechanistically analyse the plastic-metal ion interaction. These interactions are anticipated to be influenced by the chemistry of the water, which primarily affects salinity, pH, temperature, redox conditions, and other dissolved ions, and the properties of the plastic matrix, which primarily affect the surface charge, wettability, and reactive surface area) (Binda *et al*., 2021).

The sorption process is essentially influenced by the physicochemical characteristics of the medium (environmental factors), the MPs (chemical and physical properties), and the pollutant (chemical properties). As a result, the interactions between contaminants and MPs, which might be dominated by a particular contribution or possibly be constituted of numerous types of contributions, determine the sorption mechanisms between them (Menéndez-Pedriza & Jaumot, 2020). Below is a diagram by Menéndez-Pedriza & Jaumot, 2020 which illustrates factors affecting the sorption of pollutants onto MPs.

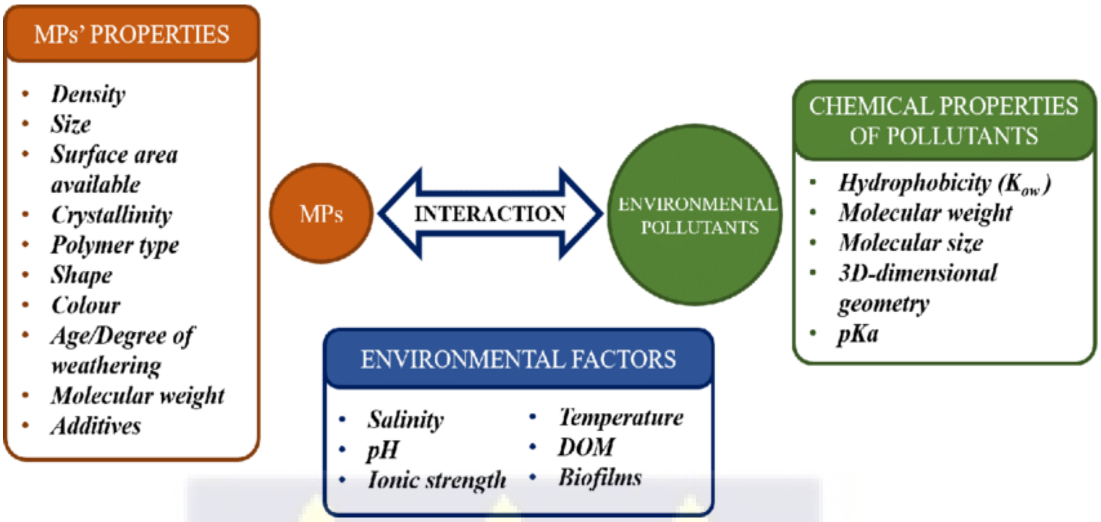


Fig. 2.5: Factors Affecting Sorption of Chemical Pollutants unto MPs (Diagram from Menéndez-Pedriza & Jaumot, 2020)

It has been observed that various MP polymer types exhibit affinity for particular metals. According to a study done in the Madeira Island, Portugal, compared to virgin polystyrene microplastics, Copper (Cu) and Zinc (Zn) showed the strongest affinity for aged PVC (Brennecke *et al*., 2016). In another investigation, the amount of Lead (Pb) and Manganese (Mn) that adsorbs to PP and PVC relative to PE, PA, and POM microplastics was greater. The degree of this adsorption was directly correlated with the concentration of these metals in the saltwater . In contrast to these results, Rochman *et al*. (2014) found no differences in the amounts of Ni, Zn, Cd, and Pb absorbed in saltwater by PET, HDPE, PVC, PP, and LDPE MPs after 12 months.

The ability of PS MPs to transport heavy metals increases dramatically with age, and the ageing process of PS MPs varies in fresh and seawater as well as in the air (Holmes *et al*., 2012; Mao *et al*., 2020). MPs' surfaces are altered by excessive weathering and ageing by rubbing against other environmental elements or exposure to UV rays. These modifications increase MPs' surface area, leading to the development of anionic active sites. These become the central locations for attracting cationic metal contaminants from the environment (Vedolin *et al*., 2018).

The pH and salinity of water affect heavy metals' sorption on MPs (Holmes *et al*., 2014; Wang *et al*., 2020b). In order to assess the capacity of microplastic pellets to adsorb heavy metals such as Pb, Cd, Cr, Cu, Ni, and Co, Holmes et al., (2014) created a salinity gradient by blending river and seawater. While Cd, Co, and Ni adsorption decreased with the salinity gradient, that of Cr increased. In general, a rise in pH facilitated their adsorption. However, salinity and pH had little impact on Cu (Khalid *et al*., 2021).

Metal adsorption on MPs is significantly influenced by the amount of dissolved organic matter in the surrounding water (Godoy *et al*., 2019). Organic material in a solution may offer extra surfaces for contaminant binding or compete with metal ions already adsorbed on MPs surfaces. Metal adsorption is facilitated by forming a thick layer of bacteria known as a "Plastisphere" on MP surfaces (Rochman *et al*., 2014).

Due to the mechanism of metal desorption, microplastics can act as point sources of heavy metals in the environment (Munier and Bendell, 2018). Environmental influences from the outside may influence the desorption of metals from the MPs in the soil. The particle size and dosage of MPs in the soil and the pH are essential variables in adsorption and desorption (Zhang *et al*., 2020).

2.5 Social Interactions

The World Economic Forum (WEF) emphasized that by 2040, the volume of plastic entering the ocean will have tripled if plastic manufacturing and use follows the current growth trajectory (Eckstein *et al*., 2019). Current urban waste management techniques fall short of lowering the amount of solid waste produced by plastic consumption (Dhir *et al*., 2021). According to reports from developing markets, excessive use of chemical additives during plastic use, disposal, and recycling (Baidu *et al*., 2017) has been linked to substantial ecological destruction (Hahladakis *et al*., 2018; Tandon *et al*., 2020).

The use and disposal of plastic materials by humans in a wide range of societal situations, along with the production of plastic materials, are some factors contributing to plastic pollution, which is anthropogenic (Thompson *et al*., 2009). Environmental plastic pollution, whether from macro, micro, or nanoplastics, is the outcome of a network of interconnected social, technical, economic, and ecological phenomena. Diverse sources and pathways determine the kind and number of materials that end up in the natural environment (Kumar *et al*., 2021). Individuals, communities, businesses, and policymakers are only a few actors in the social-environmental system that influence plastic flow (Kumar *et al*., 2021).

Because of its variety of applications and materials, plastic pollution differs from other environmental threats that are more obvious. Plastic is not a single material utilized in a few circumstances that can be addressed by a single ban (e.g., as seen for asbestos). Instead, a variety of alternative strategies aimed at various stakeholders must be pursued.

Recent studies indicate that minimising plastic pollution and simultaneously promoting sustainable consumption may necessitate a larger focus on understanding human behaviour, rather than relying just on economic incentives and disincentives as is commonly believed. (Pahl *et al*., 2017; Jia *et al*., 2019). Studying how social interventions, such as Citizen Science initiatives, might change people's views and behaviours in the environmental domain is gaining traction due to the increased public awareness of and perception of the harm posed by plastic pollution (SAPEA, 2019).

Understanding consumer behaviour may help to resolve the plastics problem. A key issue that requires attention is how consumers see product packaging that has outlived its usefulness, particularly packaging made of plastics (Adeniran *et al*., 2022). In theory, every cosumer is responsible for protecting the environment, yet surprisingly few environmentally aware consumers do their part. Although they are partially aware of the plastic pollution problem, they continue to act in an unsustainable manner (Sousa, 2023). Therefore, consumption behaviour associated with the usage of plastics is a fascinating research issue.

For efforts to reduce plastic pollution to be effective, it is crucial to incorporate a variety of well-established social science research methodologies to take into account the product and how it is used, the context in which it is used and where and when it might leak into the environment, and the actors and the decisions and behaviours that underlie this plastic use and leakage (Prata *et al.*, 2020. The effectiveness of actions will increase by understanding and systematically integrating this human dimension. This will help blend top-down strategies like legal frameworks and financial incentives with bottom-up approaches like voluntary agreements and grassroots initiatives (Yang et al., 2020).

2.5.1 Behaviour

2.5.1.1. Consumer Behaviour

Numerous sociologists think that poor environmental behaviour by humans is ultimately what causes environmental problems (Trinh, 2019; Linh *et al*., 2021). Growing awareness of ecological and environmental issues highlights the role that each individual plays in addressing the present ‘eco-crisis’ (White & Hunter, 2009). Assessing consumer behaviour of plastics is key in determining plastic waste management issues.

There is general consensus that modifying consumer behaviour appropriately can reduce the use of plastics. (Marazzi *et al*., 2020). However, the relevance of "awareness against plastic waste" and "encouraging the reuse of plastic items and the usage of environmentally friendly products" are the only assumptions made by the majority of qualitative studies (Chau *et al*., 2020). Liu *et al*. (2021), claim that consumers' use of plastic is influenced by their money, knowledge and awareness (particularly about human health), norms of the "critical mass," and situational control (such as access and infrastructure). Nevertheless, quantitative research suggests that (a) attitudes, intentions, perceived behavioural control (i.e., access) and subjective norms (i.e., social pressure) predict attitudes and behaviours related to carrying a shopping bag; and (b) these characteristics also predict intentions to reduce plastic waste. (Linh *et al*., 2021). However, Trinh (2019) found no evidence that perceived behavioural control and environmental messaging impacted the desire for alternatives to plastics. Additionally, respondents exhibit greater agreement in some locations and are more (1) uniformly quantitative; (2) directly related to the use of plastic bags. Most socio-demographic predictors note gender as a significant predictor (Hohmann *et al*., 2016; Madigele *et al*.,

2017) (i.e., women appear to use plastic bags less than men). Similar findings have been made regarding (1) age (Braun and Traore, 2015): "older people... avoid using plastic bags as a way to take care of the environment." and (2) education/income: "higher levels decrease plastic bag use." (Madigele *et al.*, 2017; Zambrano-Monserrate and Ruano, 2020).

A study by Nguyen *et al.*, 2022 aimed to provide clarity on the generation patterns of Single Use Plastics (SUP) and understand the behavior of university students as consumers. This analysis formed the foundation for proposing strategies to promote eco-friendly consumption and work towards establishing plastic-free environments within university campuses. With 1.39 g consumed daily by each student, the plastic bottle was the most consumed by students, followed by the cup (0.20 g) and the bag (0.144g) per student. Nearly all students (94.41%) had a high awareness of the effects that SUP had. Eight (2.32%) of students said they were to blame for SUP problems, which is more than four out of five. The majority of students felt uncomfortable or guilty about consuming SUP (66.57% uneasy and 15.13% guilty), and nearly one-fifth (19.50%) thought that school administrators were also to blame for the SUP issue. Approximately 25% of students said that minimising SUP was unnecessary and that it was sufficient to dispose of SUP trash properly. On the other hand, 19.03% of students favoured raising the price of SUPs and 10% advocated for a formal ban.

2.5.1.2 Theory of Pro-environmental Behaviour (PB)

Several studies have been conducted on raising awareness of environmental sustainability issues and the impact of human activity on the natural ecological environment (Gifford and Nilsson, 2014). The impact of human activity on the natural ecological environment also elevates the question of pro-environmental actions as a priority in public debates (Li *et al*., 2019). Individuals and groups can engage in environmental behaviours to reduce environmental harm and improve the environment through direct and indirect actions (Jensen, 2002). Internal and external influences impact pro-environmental behaviours (Blok *et al*., 2015; Juvan and Dolnicar, 2017). In a meta-analysis by Hines *et al*. (1987), environmental knowledge was one of the most effective predictors of ecologically friendly actions. One won't be inclined to actively care about environmental issues or behave in a pro-environment manner if they are unaware of the challenges (Gifford and Nilsson, 2014).

Pro-environmental behaviour is described as an action that causes the least amount of environmental harm and may even be advantageous to the environment (Steg and Vlek, 2009). The notion of pro-environmental activity is expanded to reduce and benefit environmental harm (Bronfman *et al*., 2015) based on understanding how behaviour affects the environment. This definition emphasizes enhancing human-influenced environmental activities while minimizing negative environmental impacts, including the release of greenhouse gas emissions the waste of natural resources, and so forth. Pro-environmental behaviour also refers to actions that enhance environmental sustainability (Palomo-Vélez *et al*., 2020). Pro-environmental behaviour relates to activities that consciously safeguard the environment and increase sustainability.

According to earlier research, having a good attitude influences one's actions towards nature and is strongly correlated with environmental awareness (Hasan *et al*., 2015; Xu *et al*., 2022; Allison *et al*., 2022). Additionally, Hasan *et al*., (2015) found a strong positive association between environmental knowledge and attitude and plastic usage. Xu et al., 2022 investigated how a Chinese rule prohibiting plastic bags affected the views and behaviour of residents and businesses. According to this study, more than

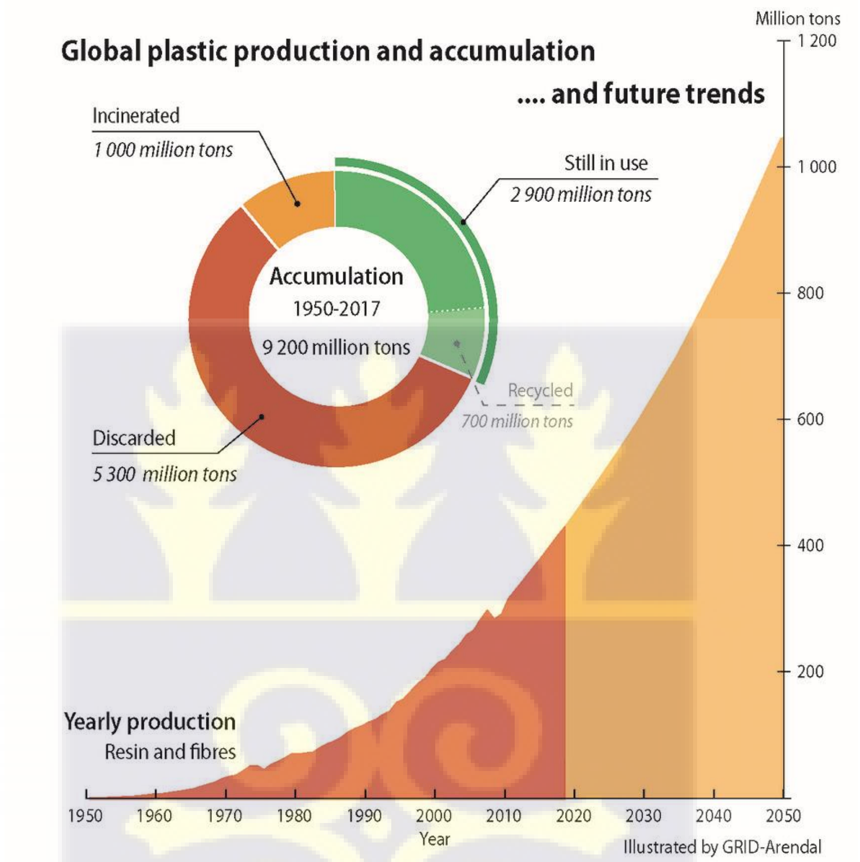
96% of respondents know the potential risks associated with plastic bags. Their findings suggest that environmental awareness has a discernible impact on behaviour in lowering plastic bag use. On the probable environmental and health consequences of plastic bags, every answer is in agreement. Effective environmental publicity fosters and strengthens environmental concerns. However, it's still essential to promote environmental awareness through broader environmental education (Cai *et al*., 2021)

The main conclusions of the study by Allison *et al*., 2022 demonstrate that, in order to promote behaviours that reduce plastic waste and prevent behaviours that increase plastic waste under a plastic bag restriction regulation in China, a combination of capability, opportunity, and motivation is needed. Focusing solely on knowledge and awareness is insufficient for behavior change. To effectively encourage behaviors that reduce plastic waste, interventions should incorporate strategies like providing information about the environmental and social consequences, using prompts and cues, offering material incentives for specific actions, and introducing relevant items into the environment. These approaches, which emphasize persuasion, enablement, and environmental restructuring, are more likely to drive the desired changes in behavior (Allison *et al*., 2022).

2.5.2 Plastic Waste Management

Geyer *et al*., 2017 estimates that 79% of plastics produced will end up as plastic waste in the environment. Figure 2.6 also shows that between 1950 and 2017, 9200 Mt of plastic waste was accumulated, and more than half of this (5300 Mt) was discarded. These trends imply that with more plastics being produced, plastic waste dumped into the environment will increase unless policies and measures are implemented to manage plastic waste.

In addition, plastic waste generation depends on plastic use and product lifespans. That is, plastic products used in construction last longer than plastics used in packaging, making packaging plastics account for 42% of plastic waste generated, as stated by OEDC, 2022. Figure 2.6 illustrates the production accumulation and future trends of plastics globally (UNEP, 2021).



UNEP (2021). From Pollution to Solution: A global assessment of marine litter and plastic pollution. Nairobi.

Fig. 2.6: Global Plastic Production, Accumulation and Future Trends. (Source UNEP 2021)

Most of the plastic waste produced ends up in the environment (marine, land and aquatic habitats). Plastic waste is ubiquitous and has been suggested to be used as an indicator for the Anthropocene era (Zalasiewicz *et al*., 2016). As per the OECD, (2022), approximately 6.1 Mt of plastic waste entered aquatic environments in 2019, with 1.7

Mt making its way to the oceans. Presently, seas and oceans are estimated to have around 30 Mt of plastic waste, while rivers have accumulated an additional 109Mt. The accumulation of plastic in rivers suggests that, despite efforts to improve plastic waste management and reduce improper disposal, the continuous flow of plastic into the oceans will persist for many years.

Plastic Pollution in Ghana is no different from the rest of the world. However, the challenges faced in Ghana are compounded by poor waste management, behaviour, and inadequate infrastructure for sustainable waste management and support for recycling (GNPAP, 2021). The effects of plastic waste littering are evident in the environment, wetlands, river banks, and beaches. These have caused environmental and health challenges as these plastics cause blockage of waterways, causing flooding, which leads to property destruction and other health risks (GNPAP. 2021).

The Ghana National Plastics Action Plan, 2021 outlines a roadmap for radical reduction of plastic pollution in Ghana. It projects that approximately 0.84 million metric tons (Mt) of municipal solid waste (MSW) plastics were generated in the country in 2020. Managed waste makes up 0.20 Mt (23.8%) of this total. The total amount of plastic waste collected is calculated to be 49%; 35% comes from official collection by municipal authorities, 11% comes from informal collection, and 3% comes from dumpsite recovery. Of these collections, 5% are recycled. Mismanagement of 0.56 Mt (66.7%) of plastic garbage is the total. This created (0.08Mt) plastic garbage, or roughly 9.5% of the total plastic waste, leaks into lakes, rivers, streams, and the ocean.

Most plastic pollution is caused by improperly collecting and disposing of macroplastics, which are bigger plastic items. However, leakage of microplastics (synthetic polymers smaller than 5 mm in diameter) from industrial plastic pellets, synthetic textiles, road markings and tyre wear also cause serious harm to the environment.

2.5.2.1 Waste Management Strategies

Government municipalities, social communities, and local authorities have adopted several methods and environmental safety laws and guidelines to direct the populace on how to dispose of plastic garbage after use (Benson *et al*., 2021). In addition, several waste management techniques have a scientific foundation, including recycling, incineration, bioremediation, and landfills. These techniques aim to maintain a clean environment and provide effective plastic trash disposal (David & Joel, 2018; Awoyera &Adesina, 2020).

Recycling

Recycling is a waste management strategy that entails collecting discarded materials and transforming them into reusable materials for the production of other valuable goods. This process, often referred to as "renewing or reusing," is implemented to protect both the environment and society. Plastics, due to their composition primarily based on carbon and incorporation of various polymers, do not naturally break down. This encompasses items like bottles, which can be melted and repurposed to create plastic furniture such as tables and chairs. (Evode *et al*., 2021). The following six procedures are used to complete this process: gathering waste plastics, sorting or categorizing plastics, washing to eliminate pollutants, shredding and resizing, identifying and separating plastics, and compounding (Szostak *et al*., 2021). When plastic waste is recycled rather than disposed of in undesirable locations, the world can benefit in many ways. One of these benefits is the protection of human life by reducing carbon dioxide and other harmful gases in the atmosphere, which can occur during incineration or combustion of wastes (Vollmer *et al*., 2020).

Incineration

The term "waste incineration process" denotes the combustion of waste materials in the presence of oxygen, also known as "full combustion" from a chemical standpoint. The end product results in the release of water vapor and carbon dioxide into the environment (Shome, 2020). Additionally, some amount of hydrochloric acid, ash, and other volatile compounds constitute the residual waste generated through incineration. Not all plastic garbage is viable for combustion; some are explosive and oxygen-heating resistant. All household trash plastics are not required to be adequately treated for incineration. We must be cautious when choosing plastics for incineration among non-combustible garbage to prevent these unforeseen explosive mishaps. Energy, commonly referred to as fuel, can be produced through the combustion of organic molecules (Evode *et al*., 2021).

Landfill sites

Plastic wastes are usually thrown into garbage bins which eventually end up at landfill sites. These land fill sites are normally, either engineered or non-engineered areas for disposal of garbage, however, non-engineered land fill sites pose an environmental risk through the seepage of leachates from these sites into aquifers, hence precautions must be taken to protect aquatic ecosystems from being contaminated by these landfill sites (Zheng *et al*., 2005). As a result, landfill sites are designed to provide a safer region for disposing of waste while protecting aquatic life and airspace. However, development of landfill sites is arduous and involves work on the part of the community, such as excavating a pit for dumping. In addition, this process is executed extremely slowly and could take more than a year (Liang *et al*., 2021).

Various techniques can be used to treat plastic trash, allowing the plastic to have a cyclical life. Through the repurposing of raw materials and the reuse of plastics, these initiatives hold the potential to achieve cost savings and simultaneously safeguard the well-being of humans, animals, and the environment. Moreover, the implementation of secure plastic waste management methods will play a role in supporting economic advancement by reducing manufacturing expenditures. Beyond its economic viability, this approach will also play a pivotal role in eliminating infectious diseases transmitted through polluted water and air (Evode *et al*., 2021).

2.5.3 Risk Perception

2.5.3.1 Theory of Risk Perception

Over the past few years, interdisciplinary research in fields like sociology, psychology, public administration, and communication has made risk perception a prominent subject of study. Environmental risk perception, according to some scholars (Sjöberg, 2010; Taround, 2014), is the public's subjective assessment and immediate experience of the environment. According to studies, environmental risk perception significantly influences attitudes and behaviours. The government's implementation of its environmental policies will be impacted by rising risk perception and risk response behaviours (Glaser, 2012).

Risk perception refers to evaluating and adopting sensory impressions or knowledge of dangers and hazards stored in a person's memory (Heidbreder *et al*., 2019). Typically, experts compare risks to the anticipated average loss (damage) per unit of time. On the other hand, non-experts view risks as a complicated, multifaceted phenomenon that influences how much of a risk is believed to be present in hazardous situations, where even the irrational expectation of loss or damage plays a supportive role. (Heidbreder *et al*., 2019). Bennet & Calman 2010 list the following as risk perception factors for non-experts: the capacity to recognise risk sources and their causes (natural or man-made); the possibility of one's own control and dominance; familiarity with risk sources; willingness to take risks; and the probability that a risk source will successfully cause a disaster; the objective impact of benefit-risk distribution; the reversibility of risk outcomes; individual experiences with technology and the natural environment; and exposure.

Sandman has stated risk perception as Perceived Risk (R) = Hazard (H) + Outrage (O). Risk perception is the arbitrary assessment made by individuals of the characteristics and seriousness of the risk. There are two parts to it: outrage and hazard. The term "hazard" refers the seriousness of the effect. Outrage (the subjective element) concentrates on a circumstance opposite to the danger dimension (Sandman, 2012).

In a Lithuanian case sample, Liobikiene and Juknys (2016) looked into the importance of values, environmental risk perception, awareness of repercussions, and willingness to engage in an environmentally friendly activity. Using interviews and questionnaires, they discovered that self-transcendence value orientation, environmental risk perception, and taking responsibility were the most significant predictors of environmental behaviour in a target population of Lithuanians aged 15 to 74 (Liobikiene and Juknys, 2016).

The outcomes of risk perception research based on various methodologies and models are crucial for directing risk management and assisting in risk reduction efforts. Studies on environmental risks related to public opinion focus on how people view and react to risks, how risks are presented and conveyed, and how risks are organized in social processes. A successful approach to managing environmental hazards is built on identifying public perceptions of environmental threats (Frewer, 2004). Understanding risk perceptions and the underlying mechanisms is crucial for better understanding how individuals evaluate risk.

2.5.4 Structural Equation Modelling

Structural equation modelling (SEM) is a potent multivariate technique used to examine and assess causal linkages. SEMs vary from other modelling techniques in examining both direct and indirect impacts on presumed causal linkages (Beran & Violato, 2010). The sophisticated statistical theory that underlies it, is its potential for assessing substantive concerns, and the ease with which it can be used all contribute to its popularity (Kaplan 2001). SEM is a group of multivariate approaches that confirms, as opposed to investigates, how accurate models are when tested against data (Byrne, 2011). Compared to traditional multivariate approaches, SEM offers three major improvements: (1) explicit measurement error evaluation; (2) estimation of latent (unobserved) variables via seen parameters; and (3) model testing, which allows one to impose a structure and assess how well the data fits a model (Novikova *et al*., 2013).

SEM is the result of combining two statistical techniques: route analysis and confirmatory factor analysis. Confirmatory factor analysis, with roots in psychometrics (Galton 1888; Pearson and Lee 1903; Spearman 1904), aims to assess psychological attributes that are not readily apparent, such as contentment and attitude. However, path analysis, which has its roots in biometrics, aimed to create a path diagram in order to determine the cause-and-effect relationship between variables. (Wright 1918).

This study uses SEM to test the hypotheses of relationships between plastic consumption, risk perception of plastics to humans and the environment, plastic waste management and knowledge of microplastics. In an investigation on the psychological underpinnings of behaviours in the public and private domains aimed at lowering household plastic use, Heidbreder *et al.*, 2022 used SEM approach to examine the causes of three potential actions that could reduce the use of plastic: buying, advocating for change, and supporting policies, based on recognised psychological concepts of behaviour that support the environment. An integrated model demonstrated that morality and logical cost-benefit analysis are both important factors in driving down plastic consumption (Heidbreder *et al.*, 2022).

Additionally, Borongan & NaRanong, 2022, from their finding on prospects and realistic difficulties related to marine plastic litter, posit that community involvement, socioeconomic activities, COVID-19 regulations for waste management, environmental governance-related waste management policies and guidelines, and community participation had a good impact on marine plastic litter leakage and remediation procedures. Furthermore, COVID-19 and socioeconomic activities, for example, environmental governance greatly and partially mediate the effects on marine plastic load leakage. However, there was no connection between environmental governance and the waste management infrastructure. The research guided how to improve environmental governance to be able to decrease marine plastic waste and meet Manila's practical issues (Borongan & NaRanong, 2022).

A study on analysis of zero plastic bag policy effect on green behaviour with structural equation modeling (SEM) method showed that the analysis of the impact of a ban on single-use plastic bags on four factors—environmental knowledge, attitude towards the environment, consumption of green products, and advertising of green products—found that three of the four factors—environmental attitude, green advertising, and green consumption—have a positive impact on green behaviour (Indah *et al*., 2021).

2.5.5 Policies and Regulations

Single-use plastics have developed into a persistent threat for many African nations. In cities and towns all over Africa, sellers indiscriminately use plastic bags. It is typical for food to be packaged in single-use polystyrene and drinking water to be sold in plastic sachets. Ghana uses over 8.2 billion water sachets annually (Stoler, 2017). An estimated 86% of Ghana's plastic waste burden is disposed of inappropriately, causing plastics to block stormwater drains, rivers and streams. Even though plastics have negative environmental effects, there are many common single-use plastics that many low-income Ghanaians rely on for clean water or as a source of income for vendors. As a result, solving the plastics problem could have significant political, social, and economic ramifications (Stoler *et al*., 2012). The effects of plastic trash on the environment and human health are frequently evaluated against the interests of plastic producers and vendors who depend on these items. Around dumpsites in Ghana's metropolitan centres, informal waste collectors have sprung up in the quest to collect, reuse, and recycle, exposing individuals, children included to the task of plastic gathering.

Ghana has been hesitant to implement regulatory measures to address plastics, in contrast to other African nations that have enacted legislative anti-plastic restrictions that target the importation, production, and use of single-use plastics. Nonetheless, a newfound focus brought about by international partnerships has bolstered national efforts. The Basel, Rotterdam, and Stockholm Conventions (BRS) NRS-Norad Project on Marine Litter and Microplastics is one of these initiatives. It seeks to increase capacity to control cross-border movements of plastic waste, provide ecologically responsible plastic waste management, and stop or lessen the generation of plastic waste.

A collection of environmental policies and legislation serves as the foundation for Ghana's plastic waste management. The Ministry of Environment, Science, Technology and Innovation (MESTI) is the leading organization handling plastic waste. However, other organizations responsible for energy, waste, sanitation, and even local government have relevant supervisory duties.

MESTI created a draft National Plastics Management Policy in 2018 and adopted a revised draft in 2021 (National Plastics Management Policy, 2021). The National Plastics Management Policy is Ghana's comprehensive solution to handling plastics sustainably to promote rapid national growth. It has been prepared and designed in the national sustainable development priorities framework to achieve the goals of the government's Coordinated Plan of Economic and Social Development Policies (2017–2024).

The policy offers a well-defined course of action for resolving the issues presented by plastic waste in the socioeconomic setting of Ghana. The National Plastics Management Policy endeavours to establish efficient management of all strategic actions in the management and implementation of plastic waste. By emphasizing the development of commercial opportunities for the reuse of plastic waste, encouraging plastic recycling, recovery, and re-manufacturing, and developing a system to reduce, recover, and reuse plastics while phasing out single-use plastics, the Policy adopts a circular economy-based management approach to plastics. The four areas of focus that underpin the policy are:

- Development of plastics-related curricula that engages the youth and encourages behaviour change in the use of plastics and its waste management;
- Cross-sectoral cooperation and strategic planning, which include creating action plans, building capacity, and setting goals for recycling, recovery, and collection;
- Creative resource mobilisation for the establishment of a circular economy, with a focus on projects such as the establishment of a database and certification system as well as extended producer responsibility initiatives. The necessity to operationalize the Environmental Tax Regime.
- Good governance, inclusivity, and shared accountability include creating procedures for gradually phasing out the plastics goods and grades that pose the most significant risk.

The first country in Africa to join the Global Plastic Action Partnership (GPAP) was Ghana in 2019 to transition to a circular plastics economy and lessen the nation's pollution and plastic waste. This was done in acknowledgement of the more specific issue of plastic waste. More specifically, GPAP is an institutional structure that promotes the execution of an action plan for plastic waste by coordinating the activities of stakeholders. In addition, a Ministerial Conference was jointly held in September 2021 by the governments of Ecuador, Germany, Ghana, and Vietnam to advance a compelling global strategy to stop marine litter and plastic pollution and guarantee clean waters for future generations. This seminar was a warm-up for the UN Environment Assembly's fifth meeting (UNEA).

The current policy initiatives to create a circular economy for plastic trash will depend on establishing effective coordination mechanisms between the various sectors, players, and governmental organizations. The National Plastics Management Policy (NPMP) appears to concentrate on land operations in its current form and does not provide the necessary connections to the maritime and other aquatic environment. Additionally, it is required to enshrine the national policy in law. Also, it's crucial to guarantee the consistency of other laws and the application of current and future legislation.

2.6 Research Gaps

In industrialized nations, several types of studies have been conducted on the impacts of MPs on various ecosystems. However, there are vast knowledge gaps in African countries (Khan *et al*., 2018). Environmental scientists must fill in the knowledge gaps about the exposure to and risk posed by freshwater MP and the related compounds. Having examined some of the pertinent literature available in the study of plastic pollution, especially in freshwater environments, and how anthropogenic activities have contributed to the harm caused by these plastics, the following areas of research need to be pursued according to the status of the science:

- Conducting studies in aquatic environments that transport MPs to the marine environment. Gathering information about microplastic presence in terrestrial habitats. Analyzing data on surface runoff and stormwater to find nonpoint sources of microplastics.

- Investigating the depositional fluxes at the air-water interface and looking into dry and wet atmospheric fallout. Performing thorough monitoring programs to determine the risk of microplastics accurately.
- MPs serve as transporters of metals and sorbed persistent organic pollutants, facilitating their bioaccumulation. MPs consequently transport a great deal of pollutants and diseases. In order to determine the ecotoxicological effects of MPs, it is necessary to elucidate their role as carriers.
- Despite the limited research on large lakes and rivers, we lack a firm understanding of the extent of plastic contamination in surface waters. Detailed monitoring data must be produced to comprehend the environmental impact of the abundance of freshwater MP.
- Determining the origins and distribution of freshwater microplastics. We still don't fully comprehend MP's behaviour in aquatic ecosystems. Modelling techniques are required to pinpoint hotspots and sinks and quantify loads based on data on their abundance. Finding key inland sources of MP and figuring out how quickly big plastic debris fragments are crucial to understanding the environmental outcome.
- Assessing the exposure to microplastics. Marine species provide evidence; thus, it seems possible that freshwater creatures will use MP as well. Unfortunately, there is a lack of data. Environmental toxicologists must ascertain how much MP is consumed by important freshwater organisms. Gaining insights into the plastic characteristics that promote their absorption and comprehending the fate of MPs within organisms, such as excretion, accumulation, and tissue

infiltration, are pivotal. Investigating these factors requires a combination of field and laboratory studies to accurately assess real-world exposure.

- Analyzing the biological impacts of exposure to microplastics. In addition to quantity and exposure, a key factor in determining an organism's environmental hazard is whether or not MP causes adverse effects in the organism. Unfortunately, one can only make educated guesses about potential sensitive endpoints because there aren't any effect studies on freshwater species: There is a high likelihood that ingested plastic particles will disrupt metabolism (starvation owing to decreased energy intake) and cause inflammation (when transferring to tissues). The exploration of MP effects on marine and freshwater species has to be significantly enhanced because this area of research has seen the least advancement so far.
- Assessing how microplastics interact with other freshwater pollutants. Toxic substances can be found in and released from plastics (e.g., monomers or plastic additives). They can also acquire environmental toxins from their environment. This could raise the ingesting organism's toxicity and chemical exposure. Because of the vastly different spectrum and quantities of contaminants in freshwaters compared to marine MP, the findings on chemicals related to marine MP (mainly POPs) cannot be applied there. The transport of chemicals from plastics to biota and the chemical burden of freshwater MP, including the rates of absorption and desorption, must thus be investigated.
- Provide a cutting-edge framework for evaluating the risk of microplastics. MP are contaminants of emerging concern in and of themselves. They may act as vectors for other pollutants and invasive species in addition to being direct and indirect stresses for the aquatic environment. Therefore, the traditional

paradigm for risk assessment must be modified to consider other things. For instance, combining the mixture toxicity of MP-associated chemicals, the regulation of the compounds' bioavailability, and the chemical transfer from polymers to biota is necessary.

To better comprehend both environmentally relevant scenarios of the threats posed by microplastics in the real world and the underlying mechanisms, research is ultimately required to link the findings in the field studies to the laboratory results.

2.7 Conceptual Framework

Based on the literature review, the current study adopts an integrated Driver-Pressure-State-Impact-Response (DPSIR) approach to explore microplastics' occurrence, the interactions of meso/microplastics with heavy metals and the driving forces of behaviour and consumption of plastic pollution in the Odaw River in Ghana. The DPSIR framework was adopted and adapted to suit the research preferences of this study.

The DPSIR framework uses a systems-thinking approach in resolving environmental issues. A systems-thinking approach to solving issues is the idea that an understanding of a system's components is best achieved through an examination of their interactions and relationships with other systems. (Arnold & Wade, 2015). A systems approach expands the decision context by taking into account multiple issues. The DPSIR framework is a systems-thinking model that makes the assumption that there are causal relationships among the interdependent elements of social, economic, and environmental systems. Numerous uses for environmental resources, including biodiversity, land and soil resources, farming systems, water resources, and marine resources (Nuttle and Fletcher 2013), have used the DPSIR framework. The social, cultural, and economic facets of environmental and human health can also be combined into one framework using the DPSIR approach. The most frequent application of DPSIR has been in environmental management to connect socioeconomic and ecological aspects (Yee *et al*. 2012).

The four main components of the DPSIR model are the environment, resources, society, and economy. Among these, "drivers" refers to possible causes of changes in the study subject, primarily to socio-economic activities (Miranda et al., 2020) and trends in industrial development; "pressures" refers to the effects of human activities on the environment and resources in their immediate vicinity as well as the natural resources and environment, which are the direct pressure factor of the research subject (Lin et al., 2023), primarily concerning the intensity of resource and energy consumption; "states" refers to the state of the research subject under the aforementioned pressure; and "impacts" refer to the influence of the system's condition on the research subject and socio-economic development (Yakovenko et al., 2023). The process of "responses" reveals the preventative measures and active policies adopted in order to promote sustainable development (Cavoli, 2021).

The DPSIR framework assesses and manages environmental problems. The driving forces are the socioeconomic and sociocultural factors that shape how people behave and how environmental pressures are increased or decreased. Human activity’s impact on the environment results in pressures. The environment's condition is known as its state or environment's state. The term "reactions" relates to how society has handled the current state of the environment. This study adapts the DPSIR framework by grouping the objectives into three categories,

- Social Interactions – Driver/ Pressure
- Occurrence – State / Impact
- Interactions with heavy metals – State / Impact

The social interactions category is linked to the drivers and pressures contributing to plastic pollution. Social interactions, in this case, refer to how plastics are being managed and the anthropological activities surrounding plastic consumption. It refers to the social interactions with plastics. Therefore, the consumption and behaviour associated with plastic use is investigated among communities surrounding the Odaw River basin. In addition, other factors contributing to behaviour, such as risk perception, waste management of plastics and knowledge of microplastics, are investigated as part of the social interactions with plastics. Social interactions in plastic use play a significant role in plastic occurrence in freshwater environments. Poor waste management of plastics leads to plastic littering, eventually ending in the aquatic environment.

Occurrence and interaction categories deal with the state (S) in the DPSIR framework. The occurrence of microplastics in freshwater environments, as described in the literature review are of two types, primary microplastics and secondary microplastics derived from disintegrated portions of macroplastics. The occurrence of microplastics in the Odaw River deals with the abundance and spatiotemporal distribution of microplastics within the Odaw River (water column and sediments). In addition, microplastic characteristics which contribute to the level of toxicity will also be investigated. The abundance and characterization of microplastics will then be used to express the ecological risk of these microplastics in the environment.

As plastics (macro, meso and microplastics) do not exist exclusively in the environment but can interact with other organisms and chemicals, the third category deals with interactions to investigate the abiotic interactions that occur in this aquatic environment (Odaw River). The abiotic interaction studied is heavy metals, although other organic and inorganic chemicals, such as some pharmaceuticals, may be present. The focus on heavy metals is because surrounding environments close to the Korle Lagoon, which forms part of the Odaw River complex, are used for e-waste recycling and dumping. These activities have resulted in the accumulation of some heavy metals in the soils around these sites (Ansa *et al*., 2017; Osae et al., 2022). This study examines six heavy metals (Fe, Hg, Pb, Zn, Cr and Cu).

The human and environmental impacts of plastics are very significant; even though this study does not directly investigate human impacts, data from occurrence and interaction of plastics (meso/ microplastics) will indirectly give the ecological risk and impacts associated with plastics. Therefore, all three categories contribute to environmental and human impact. Recommendations from this study will serve as the Response aspect of the DPSIR Framework to complete it. In addition, the information and data from this research contribute to achieving the Sustainable Development Goals (SDG). SDGs 6 (Clean water and Sanitation), 12 (responsible consumption and production) and 15 (Life below water) are directly addressed by this study and others which are indirectly linked are SDGs 3 (Good health and well-being), 11 (Sustainable cities and communities) and 14 (life on land). A diagrammatical representation of the conceptual framework can be seen in Figure 2.7.

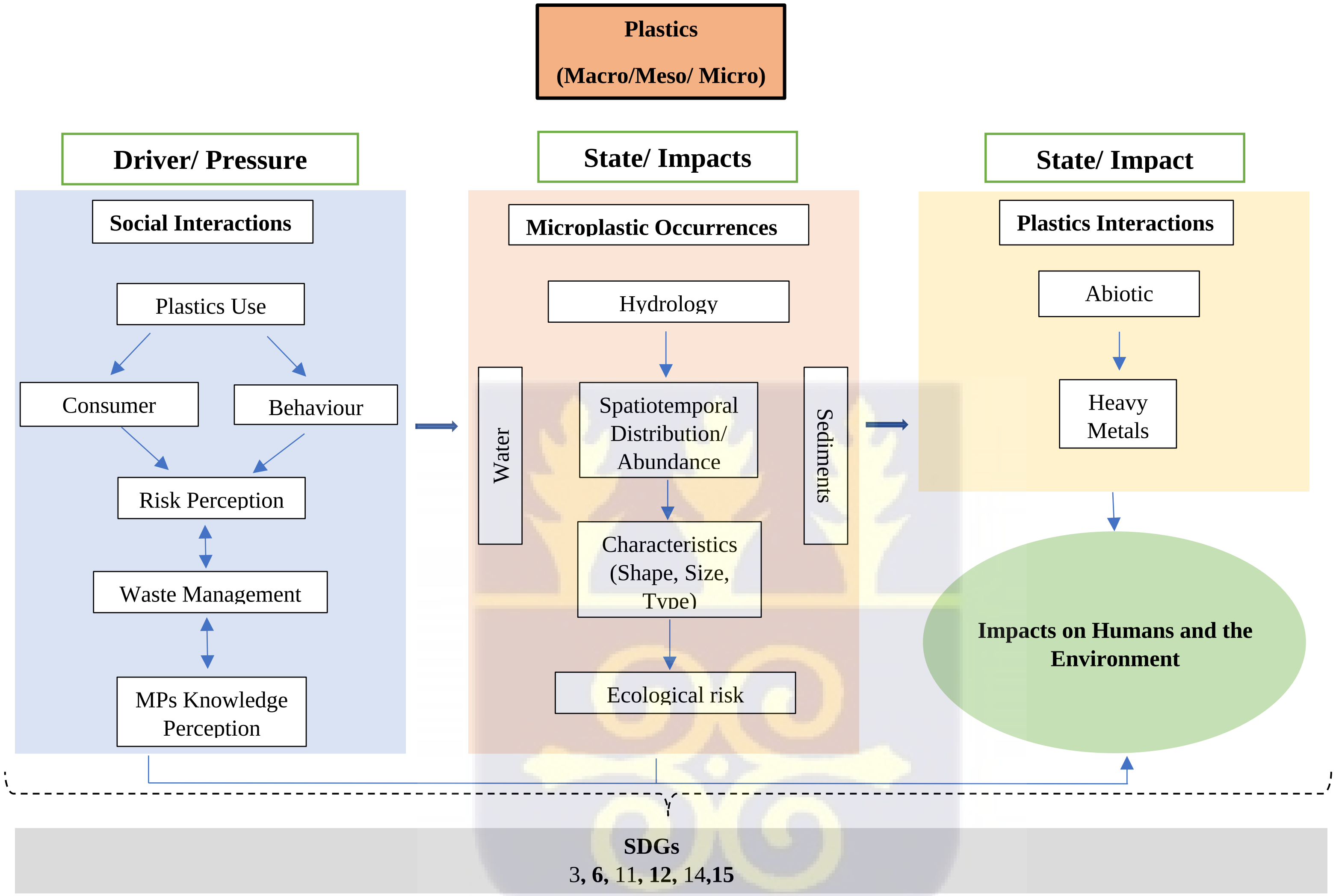


Fig. 2.7: Conceptual Framework illustrating the interplay between Social Interactions (Drivers and Pressures), Microplastic Occurrence, Microplastic Interactions (State and Impacts), and their interconnections in the study. Author’s construct adapted from DPSIR framework.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter provides background information on the study site, materials and methods used to accomplish the objectives of the study. It presents general information on the Odaw River and sampling sites along the river. It also includes information on the location's settings, socioeconomic and some physical characteristics that describes the environmental challenges faced in the area. The chapter goes on to explain the research design and various sampling sites of the distinct categories the objectives have been grouped into.

3.2 Study Area

The study area is located within latitudes 5 52′ N to 5 32′N and longitudes 0 10′ W and 0 15′. The Odaw River is about 30 km long and is estimated to have a catchment size of about 275 km^2 (Ackom *et al.*, 2020). The source of the Odaw River can be traced back to the Akuapem mountain range in the Eastern Region of Ghana, and it flows through both rural and urban regions in the Greater Accra region. The Odaw Basin encompasses the Korle Lagoon, the Odaw River itself, and the various streams and rivers that feed into it. The Odaw River is one of the major river systems in the capital of Ghana. This river is considered an urban water source since it is largely located in an urban settlement and is a source of livelihood for many who live around it. In addition, the central business and industrial hub of the Greater Accra Metropolitan Area lies within the Odaw catchment (Ntajal *et al.*, 2022).

Upstream, the major purpose of the Odaw River is to supply water for household use. On the other hand, it is also not unusual for businesses to use the river water for things like vehicle washing and making of cement blocks. It is a vital supply of water and nutrients for the cultivation of vegetable crops in the Greater-Accra Region, both upstream and downstream (MWH, 2019). Prior research on this river basin has mostly concentrated on flooding issues, e-waste, and the physicochemical features of the river, especially on the Korle Lagoon (Ackom et al., 2020a; Ansah et al., 2020; Dodd et al., 2023; Oteng-Ababio, 2012; Biney and Amuzu, 1995).

Sixty five out of the 82 officially identified slums and shantytowns are located within the immediate vicinity of the Odaw basin (MWH, 2019). Most of the drains of these settlements enter the river through natural ditches and several stormwater drains. In addition, a network of small gutters has also been put in place to serve as conduits for stormwater and domestic effluent. The river's course is mainly natural. However, some sections are constructed (e.g., Achimota to the South Industrial Area). The Korle Lagoon is the principal outlet for water in this catchment, and it also functions as a central drainage system for many parts of Accra (Amoako & Boamah, 2015).

3.2.1 General Site Description

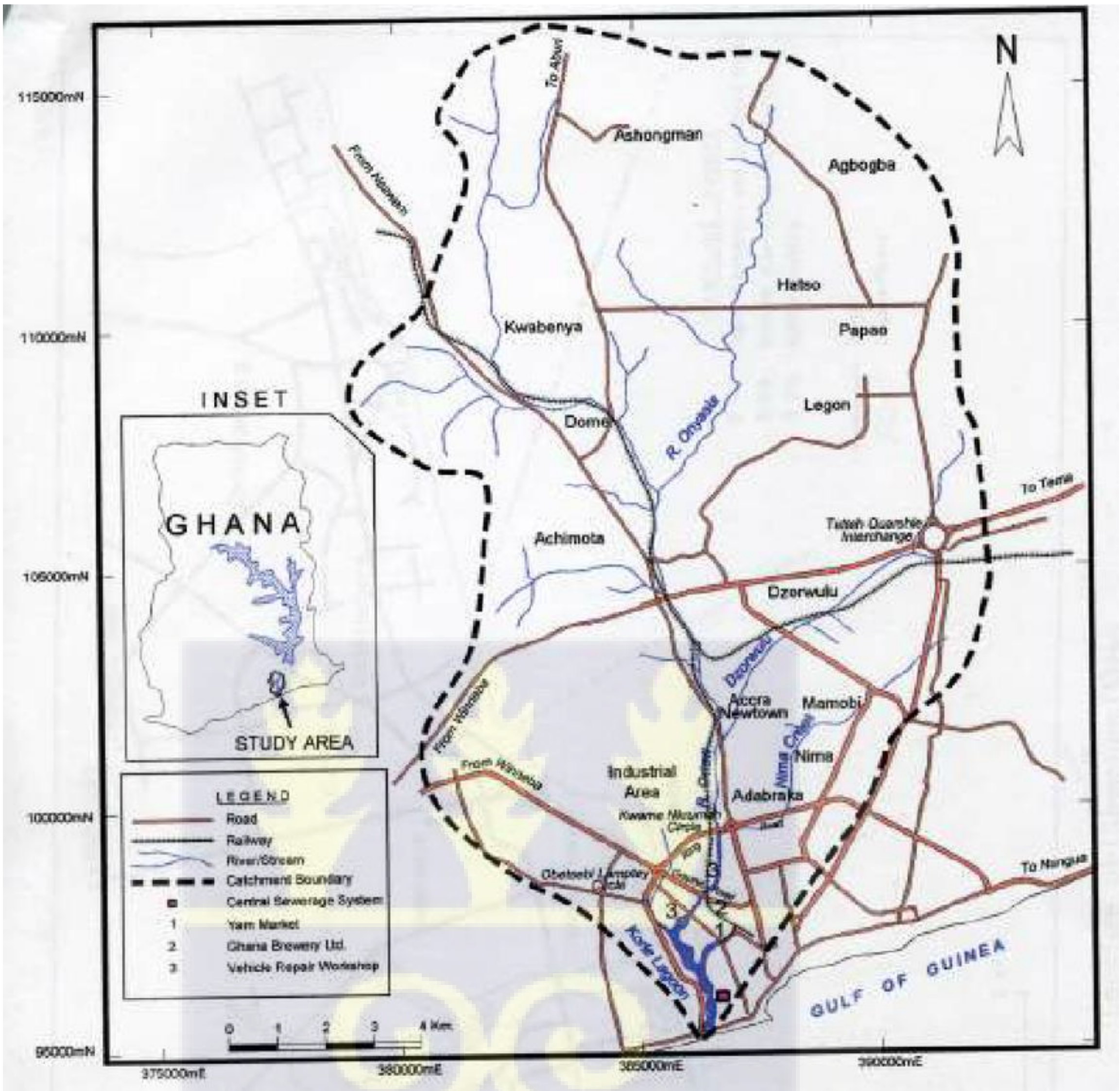


Fig. 3.1: Map of a section of Odaw River Basin showing the complex of the Korle Lagoon and the river channel with the urbanised areas of Accra. (Source: Karikari et al., 2009)

3.2.1.1 Location and Size

The Korle Lagoon is the main and only outlet for the Odaw River where it enters the Atlantic Ocean. The main tributaries that drain into the catchment of the Odaw River are Nima, Onyasia, Dakobi and Ado (Karikari *et al*., 2009). The catchment's broadest area is just over 10 m wide (Ackom *et al*., 2020). However, most of the basin's lowest-lying region is occupied by Korle Lagoon. Figure 3.2 shows the map of sampling points along the Odaw River. The river runs across the western breadth of the GAMA, from the source in the Akuapem Ranges to where it enters the ocean.

3.2.2 The Odaw River, Korle Lagoon and its Environs

The Odaw River basin is a complex of the Odaw River channel and the Korle Lagoon. The Korle lagoon has two sections (Fig. 3.1): the lower lagoon flows from the Guggisberg Bridge south to the Winneba Bridge with its discharge into the ocean, and the upper lagoon extends from the Klerp interceptor to the Guggisberg Bridge (MWH, 2019). The lagoon has a 243,292m^2 total surface area and is 2.8km long with an average width of 195.70m. Odaw, Kaneshie, and Agbogbloshie streams are the principal waterways that carry their flows into the Korle Lagoon (Karikari *et al*., 2009).

The Odaw River channel represents a major waterway that contributes to the Korle Lagoon. While there are several smaller streams connected to the lagoon, the Odaw River stands out as a major tributary. The Odaw River converges with other streams before eventually merging with the Korle Lagoon. From there, the combined waters flow into the Gulf of Guinea.

3.2.3 Climate and Vegetation

With an average temperature of 28°C, March is the year's warmest month. August, usually considered the coldest month, has an average temperature of 24°C (Danquah 2013). According to the Ghana Statistics Service (2014), relative humidity varies from 65% mid-afternoon to 95% at night.

The above annual average temperature characterises the study site as a tropical savanna climate (Codjoe & Larbi, 2015). The basin experiences two seasons: the wet season, characterised by a bimodal rainfall pattern. April and July record the highest rainfall, whiles September and October have the lowest (minor raining season), with an average annual precipitation of 730 mm. The dry season is from December to March (Ntajal *et al*., 2022).

Spatiotemporally, rainfall distribution increases toward the northern part of the Odaw river basin, with a total annual precipitation averaging 730 mm. Rainfall duration is usually short but intense, leading to flooding, especially in blocked drainage channels (Attipoe 2014).

The study area is divided into three parts and consists of the highly urbanised downstream, consisting primarily of commercial and residential zones with very little to no vegetation. The area's sparse vegetation consists of marsh vegetation surrounding the lagoon and overgrown weeds along the drain's edges (GSS, 2014). In the northwest, near the Akuapem Hills, are shrublands (from midstream to upstream) (MWH, 2018).

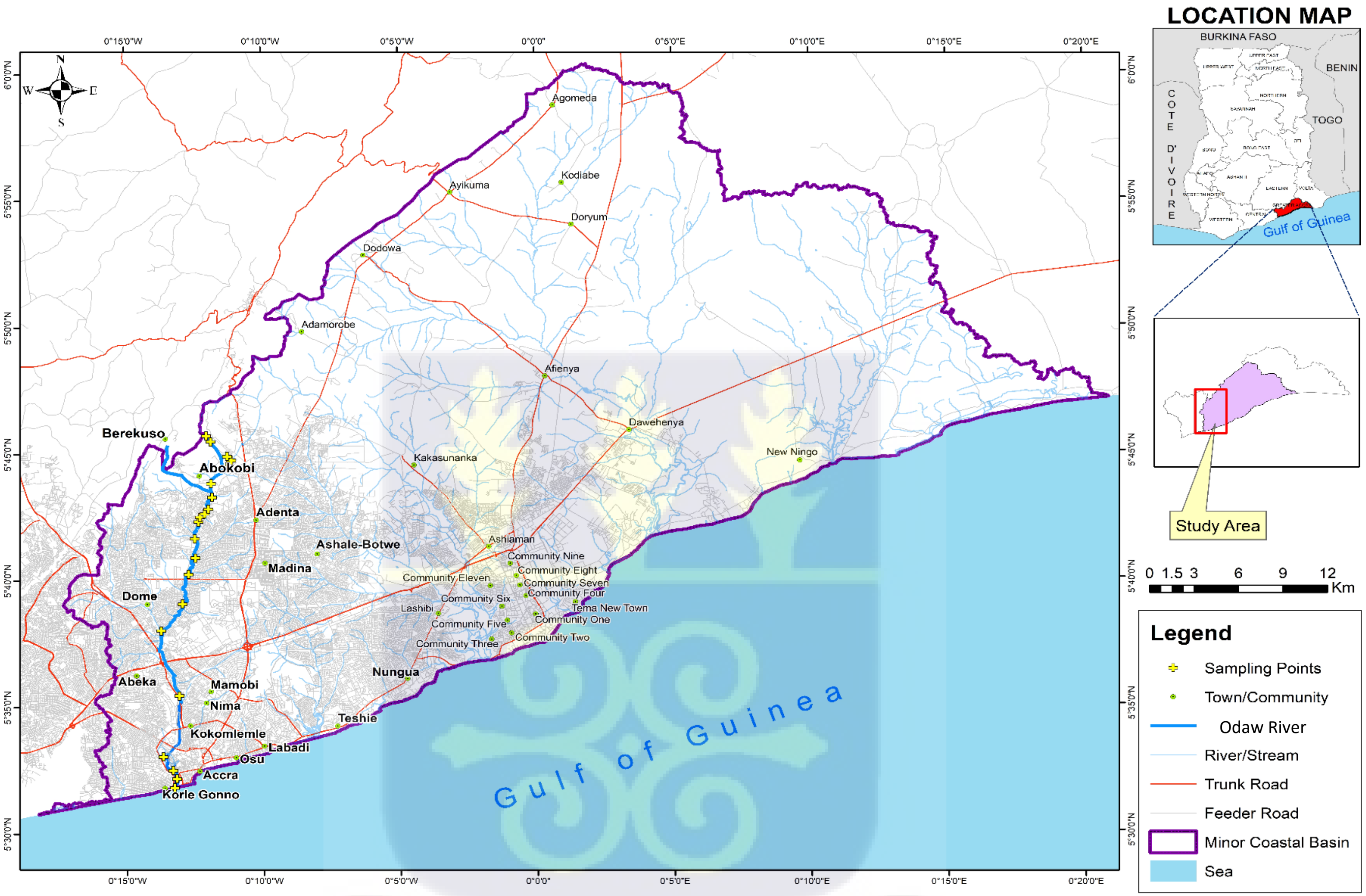


Fig. 3.2: Map of Odaw River showing sampling points

3.2.4 Relief, Drainage, Geology and Soils of the Odaw Basin

The basin's low-lying terrain ranges in elevation from 7 to 460 m above mean sea level and is characterised by successions of ridges, slopes, and sporadic rocky headlands (MWH, 2018). While the northern region of the basin is steep, the centre to the southern part is more or less level. The city's low-lying topography and the spread of slum communities make it vulnerable to flooding (Nyarko 2002). Even though the sources of all these catchments and drainage systems are located outside of the city, the risk of flooding is greatly increased by their frequent overflows during the wet season. The Odaw basin, one of the most polluted water basins in Ghana, is a conduit for waste from various sources and a sewer that is responsible for the majority of Accra's industrial and urban pollution. (Amoako & Boamah, 2015).

Precambrian Dahomeyan Schists, Granodiorites, Granites, Gneiss, and Amphibolite to late Precambrian Togo Series, primarily composed of Quartzite, Phillites, Phylitones, and Quartz Breccias, make up the geology of the basin (MWH, 2018). Additional geological formations identified are sandstone, shale, and interbedded shale-sandstone with gypsum lenses (MWH, 2018). The soils in the research region can be classified into four primary groups: lateritic sandy clay soils, alluvial and marine mottled clays, residual clays and gravels generated from weathered quartzites, gneiss and schist rocks, and drift materials resulting from deposits by windblown erosion. In addition, alluvial "black cotton" soils are found in pockets in many low-lying, poorly drained locations (MWH, 2018). These soils can expand and contract, have a high organic content, and pose serious challenges (GSS, 2014).

3.2.5 Demographic and Socioeconomic Characteristics

There are seven Metropolitan, Municipal and District Assemblies (MMDAs) located within the Odaw catchment. These are the Accra Metropolitan Assembly (AMA), the largest MMDA, Ablekuma Central, Ga East, Ga West, Adentan Metropolitan Assembly and the Akuapem North District Assembly. A total of 4 million people live in the basin, while an additional two million often visit the area to engage in various socioeconomic activities (MWH, 2018). The area is also plagued by recurrent flooding, with an estimated 30% of the population living in at-risk informal settlements that frequently flood (MWH, 2018). Small companies and retail marketing constitute the catchment's primary economic activities. The Odaw catchment area contains over 80% of Accra's industrial areas (Amoako & Boamah, 2015). Micro-retail stores, auto repair businesses, refrigerator repair shops, etc., are along the river's drainage. These MMDAs are hubs for important industrial, economic, financial, cultural, and transportation activities. Enterprises, situated near waterways, contribute to the clogging of the drainage systems, which causes floods in the neighbourhood. Within the midstream portions of the river are located vegetable farms which are irrigated with water from the river. There are other urban farms around the Airport residential area, a tributary of the Odaw River (Ansa et al., 2017).

3.2.6 Pressures of Odaw Basin

3.2.6.1 Pressures of Urbanisation

The Greater Accra Metropolitan Area's (GAMA) dominance as a centre for administration, education, industry, and commerce causes many people to migrate from other regions to the capital. Around 37% of the population increase can be attributed to migration from rural to urban areas (GSS, 2023). In general, the MMDAs around the basin have a burden of rapidly growing population, which, coupled with poor development and inadequate environmental sanitation management, has contributed to the poor state of the river basin. Almost all ecosystem services the river basin provides are at their minimum because of the tremendous strain on the basin supply (GSS, 2023).

3.2.6.2 River Basin as Drainage System

The Odaw basin acts as a drainage system for communities around the basin. It drains 60% of the city of Accra (Ackom 2020). Natural and significant stormwater drains make up Accra's drainage system. A system of small drains known as gutters has been installed to act as both a stormwater drains and a conduit for domestic sewage. Although the river's route is natural, certain sections have been constructed (such as Achimota to Agbogbloshie). The Korle Lagoon serves as this catchment's main water exit, and it also serves as a primary drainage system by discharging its contents into the sea. Due to excessive siltation and gravity-based drainage with most drainage basins uncovered, the current drainage system has become increasingly shallow over time (Ntajal *et al.*, 2022).

The Odaw River has experienced challenges of flooding in recent times. For the past three decades, there has been a problem managing urban stormwater, which has led to what might be called persistent floods. The flood that rocked Accra on June 3, 2015, which resulted in a gasoline station explosion and the deaths of 152 people, extensive property damage, and the displacement of hundreds of people, was a typical flood disaster that has occurred recently and had a significant impact (Amoako & Boamah, 2015). Key stakeholders and researchers have identified some causes for flooding in Accra, including increasing rainfall intensity, poor surface water resource management, unchecked urbanisation, residential development in flood-prone areas, and perceived or actual impacts of climate variability and change and poor sanitation (Ackom *et al*., 2020).

3.2.6.3 Pollution and Sanitation

Pollution influx from activities of densely populated towns near the drain or channel threatens the Odaw River and Korle Lagoon. Most drains are used as garbage sites, especially in busy, underdeveloped neighbourhoods where large trash cans are located close to open spaces (Abu & Codjoe, 2018). Several areas are severely overgrown with weeds and bushes, and severe erosion has damaged some drains and culverts. Drains near the city's centre, where shops, marketplaces, restaurants, and truck parking, are filled with stagnant water. In the industrial districts, no maintenance is done to remove the trash and silt, which leads to flooding (MWH, 2018).

The lagoon's banks serve as a dumpsite for solid waste. At the Abossey Okai road, aged equipment and abandoned vehicles are dumped in open areas. Garages and workshops can be found in the lagoon's catchment area. The yam market's proximity along the lagoon's banks increases the pollution burden. The septic tank effluent treatment facility is located about 200 meters to the west of the lagoon's mouth. A sewage outfall is close to the lagoon's mouth on the east side (Karikari *et al*., 2009).

Due to poor sanitation, including the dumping of waste and human excreta (open defecation is an everyday activity along the drain), and in other cases, complete neglect, the channel/drain is in poor shape (Karikari *et al*., 2009). In addition to being densely inhabited, roughly 80% of Accra's industries are situated in the Odaw-Korle complex's lower drainage basin. As a result, the lagoon's natural ecology has been disrupted by large volumes of untreated industrial waste being dumped into it, which has caused severe pollution and an excess load of nutrients that has caused eutrophication, which has led to the extinction of the majority of aquatic life forms (Ansa *et al*., 2017).

3.2.6.4 Environmental and Human Impact of Pollution along the Odaw River

The underlying impact of the poor sanitary conditions of the Odaw River has resulted in several environmental and human health impacts. Ntajal *et al*., 2022 stated that in 2016, the GAMA experienced an annual incidence rate of diarrheal illnesses (including cholera, typhoid, and dysentery) of about 25.6%. For instance, in Ghana, cholera was reported in over 28,974 cases and 243 deaths in 2014; over 98% of these cases and deaths were found in the Greater Accra Region, notably in the Odaw River watershed, which includes the Accra Metropolitan Area (Ohene Adjei *et al*., 2017). Food and water pollution, inadequate hygiene, and sanitation are some of the underlying causative factors.

3.2.7 Study Approach

This study's research strategy used the exploratory and explanatory case study approach. This method was adopted because the case study approach is constructive when it is necessary to thoroughly understand an issue, event, or phenomenon of interest in its natural, real-life setting (Yin, 2009). The case studies approach, which also allows for both quantitative and qualitative data analyses, supports not only the exploration or description of the data in a realistic context, but also the explanation of the complicated nature of real-life scenarios that may not be well represented by survey or experimental research. This approach is accepted as a single-case or multiple-case study method (Crowe *et al*., 2011). The single case study is limited to analysing a single instance or a subsection of a unit (Crowe *et al*., 2011). The Odaw River Basin was the subject of this study's single case study methodology.

3.3 Sampling Locations

Sampling locations along the Odaw river were selected according to the category of objectives of the study (Occurrence, Interaction with Heavy Metals and Social Interactions).

The sampling sites in the study have been categorised into three zones: Downstream, Midstream, and Upstream. Each zone represents different land use, land cover characteristics, and economic activities.

The Downstream zone is predominantly associated with commercial activities. It serves as the location for Ghana's infamous e-waste dumping and recycling site. Human activities heavily impact this area and exhibit higher pollution and contamination.

The Midstream zone comprises residential and agricultural areas along the Odaw River. Informal settlements are also prevalent in this zone, particularly near the riverbanks. The land use in this area is primarily dedicated to housing and agriculture, with a moderate level of human activity and associated environmental impacts.

The Upstream zone is considered a pristine area and serves as a control in the study. It experiences less human activity and has minimal impact compared to the other zones. This area provides a baseline condition for assessing the effects of human activities on the river's ecological health and serves as a reference point for comparison.

By grouping the sampling sites into these zones, the study aims to capture variations in land use, economic activities, and human impacts, allowing for a comprehensive analysis of the different levels of pollution and contamination in the study area.

3.3.1 Occurrence

In order to determine the occurrence of microplastics in the Odaw River, surface microplastics sampling in water and sediments were collected at 16 sampling locations along the Odaw River. Water and sediment samples from these 16 locations (SSP1–SSP3 and SP1-SP13), from the river's source in Brekusu to the mouth where it enters the Atlantic Ocean at Korle Gonno, were selected as investigation zones. Locations of MPs sampling sites are listed in Table 3.1 and illustrated in Fig. 3.3, respectively. The sampling points were chosen to reflect four land use land cover zones (Industrial/commercial, residential and agriculture, periurban and rural) of the Odaw River Basin. Additionally, sampling was done below and above the confluence of the river.

Microplastics were collected on bridges over the river. According to Kataoka *et al*., 2019, although boats and ships are the main means of collecting microplastics in rivers and seas, bridge surveys on rivers are useful as well since the microplastics can be securely gathered independent of the flow dynamics. (e.g., flooding). Samples were taken bimonthly for one year, and sampling was done in June, August, October, December, February and April 2022-23. Therefore, a total of six field sampling trips were done in a year.

In addition to collecting MPs samples, seven water quality parameters (pH, turbidity, dissolved oxygen, conductivity, salinity, temperature, and total dissolved solids) were also recorded at each sampling site. These additional parameters provide supplementary information regarding the water quality conditions at the respective sampling locations.

Table 3. 1: Sampling site codes, locations and coordinates for sampling points

Sampling site	**Location**	**Latitude**	**Longitude**
SSP1	Korle Gonno (Estuary)	05°31'50.0"N	0°13'15.9"W
SSP2	ICGC	05°33'16.3"N	0°13'52.4"W
SSP3	Agbogbloshie	05°33'07.1"N	0°13'29.9"W
SP1	Avenor	05°34'47.4"N	0°13'05.5"W
SP2	Alajo	05°35'26.7"N	0°13'02.8"W
SP3	Abofu Achimota	05°36'47.3"N	0°13'36.1"W
SP4	Christian Village	05°38'27.8"N	0°13'15.2"W
SP5	Haatso Transitions	05°40'04.2"N	0°12'50.6"W
SP6	Cosway	05°41'16.4"N	0°12'24.2"W
SP7	Agbogba	05°42'01.5"N	0°12'25.5"W
SP8	Pantang	05°42'05.5"N	0°12'00.6"W
SP9	Abokobi	05°43'50.3"N	0°11'50.3"W
SP10	Teiman	05°44'59.6"N	0°10'57.1"W
SP11	Kuotam	05°44'33.00"N	0°11'14.6"W
SP12	Brekusu 1 (Source)	05°45'00.2"N	0°13'45.0"W
SP13	Brekusu 2	05°44'56.7"N	0°13'28.5"W

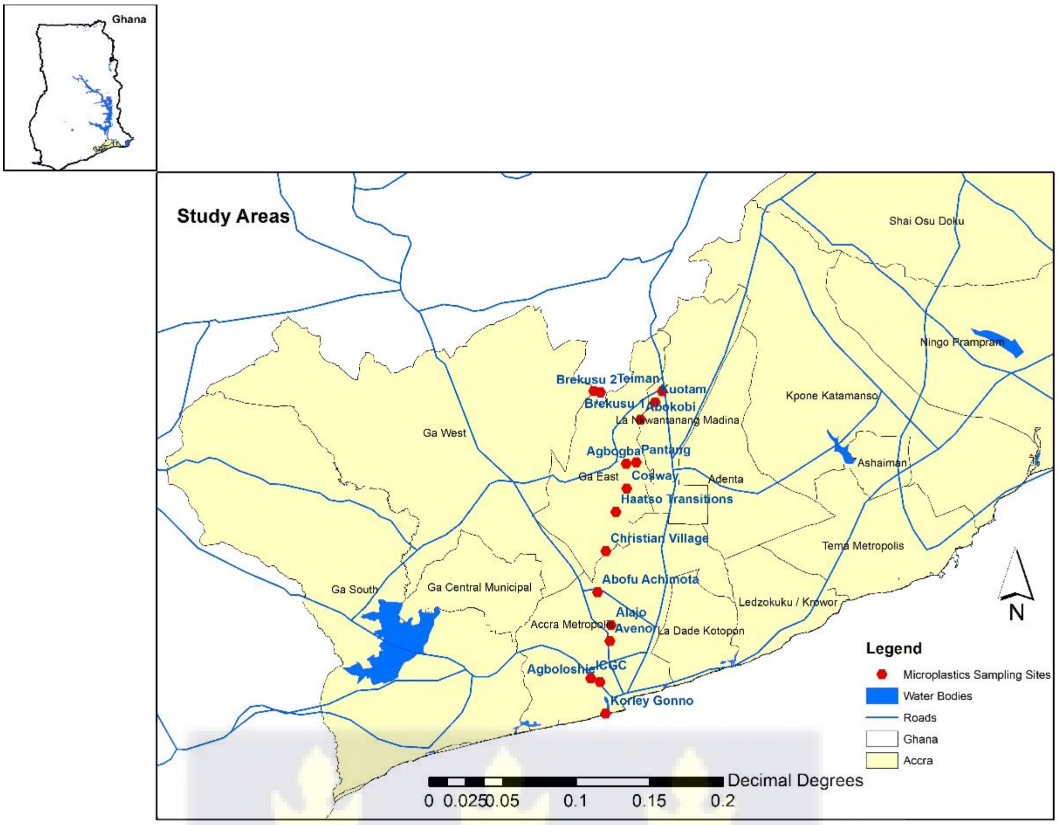


Fig. 3. 3: Map indicating sampling points for water and sediments along the Odaw River Basin

3.3.2 Interactions with Heavy Metals

For interaction of heavy metals with plastics and sediments, sampling of sediments and plastic fragments (meso and microplastics) was conducted in February 2023 at seven locations along the Odaw River, downstream (Korle Beach (estuary), Korle Lagoon and Agbogbloshie), midstream (Christian village and Haatso) and upstream (Brekusu Stream and Brekusu River source). Fig. 3.4 and Table 3.2 show the map and coordinates of the sampling points.

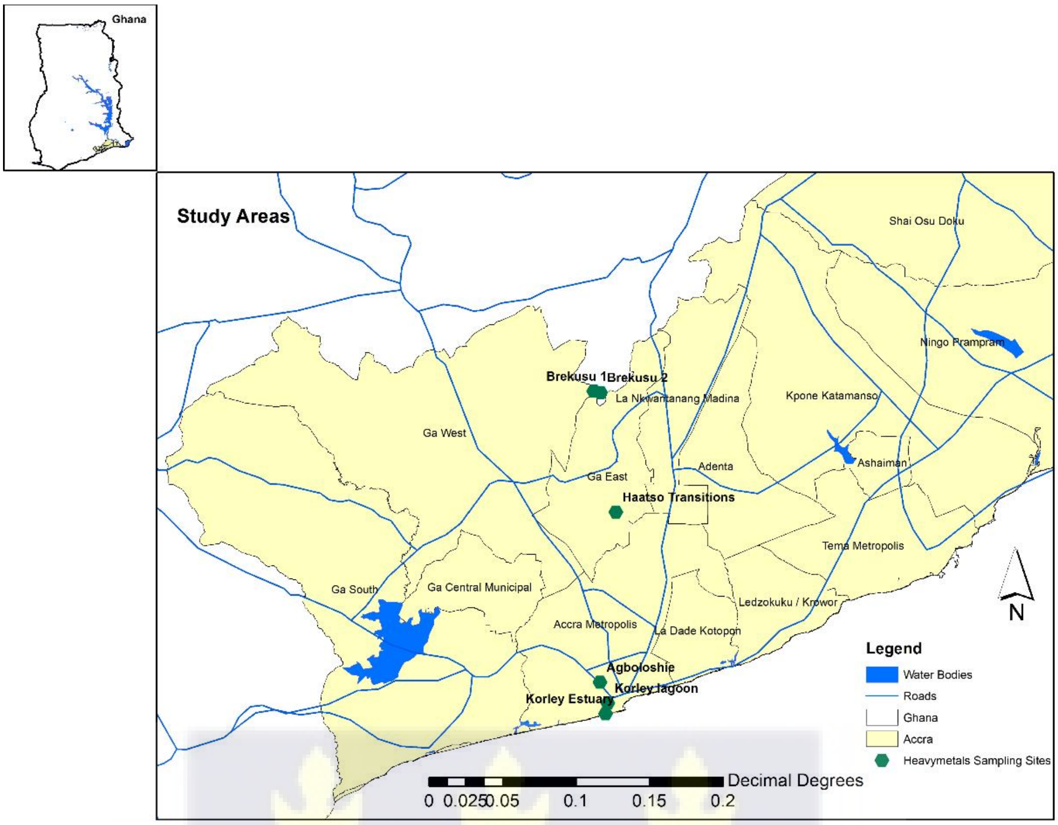


Fig. 3. 4: Map of sampling locations for heavy metals interaction with meso/ microplastics along the Odaw River Basin

Table 3. 2: Coordinates of Sampling Locations for Heavy Metals Sampling

Sampling site	**Location**	**Latitude**	**Longitude**
KB	Korle Beach	05°31'50.0"N	0°13'15.9"W
KL	Korle Lagoon	5°32'16.04"N	0°13'10.34"W
AG	Agbogbloshie	05°33'07.1"N	0°13'29.9"W
CV	Christian village	05°38'27.8"N	0°13'15.2"W
HF	Haatso Transitions	05°40'04.2"N	0°12'50.6"W
BR	Brekusu 1 (Source)	05°45'00.2"N	0°13'45.0"W
BS	Brekusu 2	05°44'56.7"N	0°13'28.5"W

3.3.3 Social Interactions

This study's surveys focused on four settlements within the Odaw River catchment area: Old Fadama, Christian Village, Haatso, and Brekusu (Figure 3.5 and Table 3.3). These specific communities were deliberately selected due to their proximity to the Odaw River, which influences their interaction with the river, the connection of their drainage systems to the river, and the accumulation of waste in or near the river. Brekusu, located upstream in the Akuapem Hills of the Eastern Region, represents rural settlements in the periurban area along the river. In the middle section, Haatso and Christian Village represent urban residential and agricultural areas along the river. Old Fadama, positioned downstream, is a residential settlement within the business hub of GAMA, representing the commercial space surrounding the river catchment. Three of the selected settlements are classified as urban poor and middle-class communities within GAMA. Over 80% of Accra's industrial zones are downstream of the Odaw catchment area (MWH, 2019). The primary economic activities in these towns, which constitute the downstream catchment area, include retail marketing, small businesses, farming, and other formal employment opportunities. Various enterprises, such as micro-retail stores, auto repair shops, and refrigerator repair businesses, are situated along the drainage systems connected to the river (Dodd *et al*., 2023). These businesses, located near waterways, significantly contribute to the obstruction of the drainage systems, leading to flooding in the surrounding neighborhoods (Ntajal *et al*., 2022).

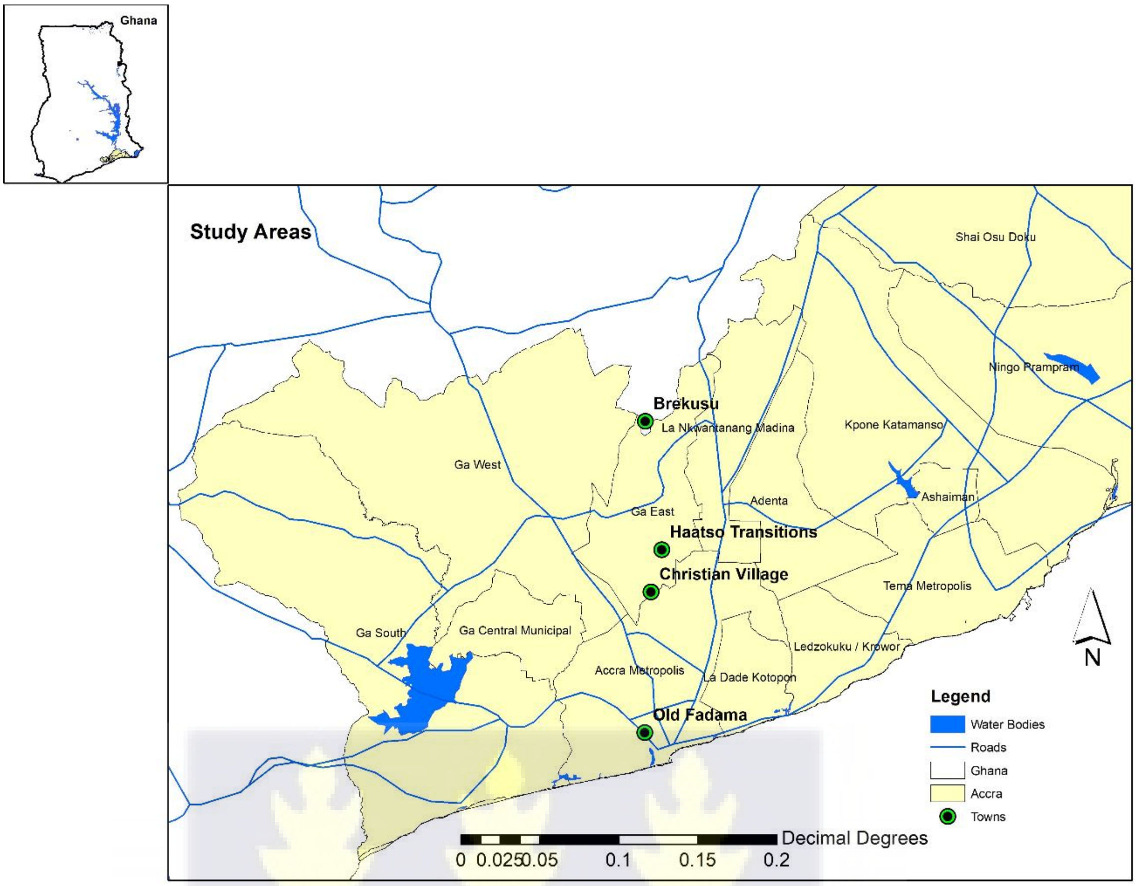


Fig. 3. 5: Map of Sampling locations along the Odaw River Basin

Table 3. 3: Coordinates for Sampling Locations for Social Interactions Survey

Location	Lat	Long
Old Fadama	05°33'07.1"N	0°13'29.9"W
Christian village	05°38'27.8"N	0°13'15.2"W
Haatso Transitions	05°40'04.2"N	0°12'50.6"W
Brekusu	05°44'56.7"N	0°13'28.5"W

3.4 Methods

3.4.1 Methods to Determine the Occurrence of Microplastics

Although there is currently no universally accepted standard methodology for the analysis of microplastics (MPs), a commonly used procedure involves the following steps: (1) collection of sample MPs; (2) isolation of MPs through digestion, separation, filtration, and drying; (3) visual identification of MPs; (4) characterisation of MPs using procedures such as Fourier Transform Infrared Spectroscopy (FTIR), Micro-Raman, and Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS); and (5) assignment of the identity of MPs (Ribeiro-Claro *et al*., 2016).

This study adopted a revised protocol developed by the National Oceanic and Atmospheric Administration (NOAA) to collect and prepare MPs samples. Based on the guidelines provided by NOAA in 2015 (Masura *et al*., 2015), this protocol serves as a framework for standardising the procedures used in the present study.

3.4.1.1 Sample Collection

Sediments

Sediment samples were collected with Vanveen grabs from bridges across the river. Approximately 500g of sediment from the grab was collected at a depth of 5cm-10cm from each sampling site. Samples collected by the grab were scooped with a stainless-steel spoon into aluminium foils, placed in a plastic ziplock bag, labelled, packed, and transported to the laboratory.

Water

Surface water sampling was done using the bulk sampling method (when a sample is acquired in bulk, its entire volume is obtained without being reduced throughout the sampling process) (Dubaish and Liebezeit 2013). Barrows *et al*. (2018) state that jar sampling is a widely employed approach for gathering microplastic samples from water bodies. This method facilitates the collection of microplastic particles of diverse sizes, enabling a comprehensive analysis of microplastics within a broad range. The effectiveness of detecting microplastics in jar samples is largely contingent upon the detection methods utilised in the laboratory. The size range of particles that can be identified depends on the capabilities of the analysis techniques employed during the examination process.

The significance of capturing smaller-sized microplastics in jar samples should be emphasized, especially since particles below 150 µm have been recognised as biologically relevant, originating from sources like tires (Covernton *et al*., 2019). Nevertheless, one limitation of the jar sampling method is that it typically collects a relatively small volume of water, often just one or two litres. Consequently, there might be instances where the concentration of microplastics in the sampled river falls below the detection limit of the jar sampling technique, resulting in a concentration level of zero in many samples (Barrows *et al*., 2018). Notably, these zero concentrations do not necessarily indicate the absence of microplastics in the water body; rather, it suggests that the concentration may not be high enough to be detected using the specific jar sampling technique (Barrows *et al*., 2018).

With a metal bucket and string attached, surface water samples (depth of 5cm-15cm) were collected from bridges across the river and transferred into in two litre glass jars with a funnel. Samples were collected in triplicate from all sites (upstream, midstream and downstream) and transported to the laboratory for further analysis.

3.4.1.2 Sample Processing

In the lab, an adapted National Oceanic and Atmospheric Administration (NOAA) laboratory technique was employed to analyze water and sediment samples for the study of microplastics, as detailed by Masura et al. (2015) and Rodrigues *et al.* (2018).

Water

The water processing consisted of sieving and wet peroxide oxidation (digestion) (depending on the condition of the water, i.e., in the presence of organic matter, 10ml - 20ml of H_2O_2 was added; in the absence of organic matter, density separation was made). Sodium Chloride (NaCl) was used for density separation, and vacuum filtration was done. One litre of water in triplicates was digested to analyse the samples using wet peroxide oxidation (30% H_2O_2) to remove organic matter when needed at a temperature of 75°C. Following a 12-hour period of reaction at ambient temperature, a density separation method is employed using 150g NaCl / L of distilled water.

MPs were able to float whereas heavier inorganic material settled to the bottom due to density separation. After at least 24 hours of density separation and settling, MPs were extracted by vacuum-filtration using glass fibre filter paper (GF3 grade glass microfibre filter, 1.2 μm). After filtration, all possible microplastic filter materials were retained on the filter paper. Prior to adding the filter paper, the petri dish was rinsed with distilled water and covered with aluminium foil. The filter paper was then placed in the oven to dry at 50°C for 24 hours.

To prevent samples from coming into contact with other plastic items during the separation and identification of microplastics and prevent experimental errors, all experimental equipment was thoroughly cleaned with distilled water. Samples were covered with aluminium foil to prevent the influence of dust and fine fibres in the air on the experimental results.

Sediments

The wet sediments were dried at 60°C for five days. Following drying, the sediments were sieved (5mm sieves) to remove any residue larger than 5mm. After drying and sieving, 50g of sediments was weighed into a beaker and 60 ml of 30% H_2O_2 was added and stirred with a stainless-steel spoon; 500 ml of NaCl separation solution was added for density separation. After 24hrs of settling, the supernatant was transferred to a 1L beaker and filtered with a fibre glass filter paper through a vacuum filtration pump. The remaining process followed the same procedure described above for water processing.

Identification

Microscopic Examination Characterisation of MPs

In the study, visual inspection was the primary method for identifying and quantifying microplastics (MPs), although chemical characterisation was conducted subsequently. The samples were visually examined using a stereomicroscope (model CP745LED Trinocular) mounted with a LC-15 NDMI Digital Camera produced by Labomed Inc. The isolated microplastic particles were then carefully counted and classified based on three main categories: size in µm (categorised as <50, 50-100, 100-200, 200-500, 500-1000, 1000-3000, 3000-5000, and >5000) using a built-in calibration scale on the microscope, shape (classified as fibre, fragment, pellet, bead, and film), and colour (identified as black, red, blue, white, yellow, transparent, and others). This meticulous categorisation enabled a comprehensive analysis of the microplastic samples, providing insights into their characteristics and distribution.

Polymer Type Identification

To validate the identification of microplastics (MPs), a Fourier transform infrared spectroscopy (FTIR) was utilised. To determine the polymers, MPs were analysed using a micro-Fourier transform infrared spectroscope (Spectrum Two with Spotlight 200i, PerkinElmer, Waltham, MA, USA). The most frequently encountered particle categories were selected for the analysis, with a random sampling approach applied at each sampling location. A total of 50 particles were chosen for analysis, with particle sizes ranging from 5 mm to 1 mm.

The software used for spectral analysis and comparison was Omics software. This software allowed for matching the IR spectra of the unknown particles with reference IR spectra. A spectral match quality index of greater than 50% was considered for positive identification, while lower match percentages were considered inconclusive or unidentified.

3.4.1.3 Quality Assurance and Quality Control

A number of precautions were taken in the lab to prevent conceivable background contamination. Wearing cotton lab coats and gloves was required for all laboratory tasks. Prior to use in the experiments, all of the study's solutions were filtered. Tools, glasses, and containers were washed in distilled water and covered with aluminium foil after each process. All synthetic clothing was rejected during the microscopic examination in order to minimise contamination.

3.4.1.4 MPs Ecological Risk Assessment

The formula used to assess the risk index for polymers in this study was developed by Lithner *et al*., 2011.

$$H = \sum(Pn \times Sn) \qquad (1)$$

The Polymer risk index (H) of a polymer is determined based on its hazard score (Sn) and the ratio (Pn) of the polymer's concentration among various types of microplastics to the total microplastics concentration. Different polymers have distinct hazard scores (Sn); for instance, polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC) have hazard scores of 1, 11, 30, and 5001, respectively (Lithner *et al*., 2011).

To assess the pollution level in connection with microplastic concentration, the Pollution Load Index (PLI) was examined (Tomlinson *et al*., 1980; Liu *et al*., 2022). The PLI model is established based on the relationship between PLI and microplastic concentration (Ci) at each sampling location, and it is summarised as follows:

$$\mathrm{PLI} = \sqrt{}\mathrm{C_i/C_{oi}} \qquad (2)$$

$$\mathrm{PLI_{zone}} = \mathrm{n}\sqrt{}\mathrm{PLI_1PLI_2 \ldots PLI_n} \qquad (3)$$

where the lowest MP concentration at each sampling location is denoted by Coi. PLI values are often calculated using the Coi (0.01 particles/L) as the minimal average concentration, according to studies by Isobe et al. (2014) and Xu et al. (2018). Table 3.4 lists the risk categories that match the hazard scores and PLI. The n-PLI was used to determine the PLI of the region with the various land cover types (PLIzone) for each sampling station in those areas. Table 3.4 shows the risk level and categories for Pollution Load Index and Risk Index for Polymers.

Table 3. 4: Risk Level Criteria for Risk Index of Polymer (H) and Pollution Load Index (PLI) (Haberstroh *et al*., 2021; Wang *et al*., 2020)

Polymer Risk Index [a] (H)	Pollution Load Index[a] [b] (PLI)	Risk Level Criteria	
<10	<10	I	Low pollution
10-100	10-20	II	Moderate pollution
100-1000	20-30	III	High pollution
>1000	30-100	IV	Extremely high Pollution

[a] Risk category (H) is taken from Xu *et al*., 2018.

[b] Risk category (PLI) is taken from Wang *et al*., 2020 and Lithner *et al*., 2011.

3.4.1.5 Data Analysis

The microplastic particle counts in water samples were expressed as items/L, whereas in sediment samples, they were expressed as items/50g of dry sediment. Statistical analyses were carried out using Microsoft Excel and SPSS software. To compare the mean abundances of microplastics among various seasons and spatial locations, the Kruskal-Wallis test was used, based on the outcome of the descriptive normality test. This test was preferred because it is a non-parametric test and does not assume that the groups follow a normal distribution and is also less sensitive to outliers, enhancing its robustness in this context (Smalheiser, 2017). These tests are appropriate for comparing non-parametric data and helped assess potential variations in microplastic abundances across different conditions and locations in the study.

3.4.2 Methods for Interactions of Heavy Metals with Microplastics and Sediments

3.4.2.1 Sampling

At each sampling point, sediments and meso/microplastics from sediments were collected from three locations. The approximate distance between these sampling locations was 5 m. Where sediment samples were inaccessible, samples were collected from the river's floodplains using a stainless spoon at a depth of 5cm-10cm. A Vanveen grab was used to collect sediments from the river at a depth of 5cm-10cm. The scooped sediments were carefully placed into ziplock bags. Additionally, meso/microplastics fragments were picked from the flood plains and in the sediments from grab with tweezers and collected in separate zip lock bags. To maintain sample integrity, the collected samples were transported to the laboratory in ice coolers to prevent degradation or contamination.

3.4.2.2 Sediment Sample Preparation and Digestion

Sample Preparation

The sample preparation and digestion procedures were conducted in accordance with the techniques outlined by Chama et al. in 2014. In a sterile setting, every sediment sample was allowed to air dry. Using hand gloves, additional organic debris, such as wood, shells, and others, was removed from the samples. Using an agate mortar and pestle, the samples were manually ground up and then sieved through a 2 mm sieve, and homogenised sieved samples were kept in air-tight Ziploc bags for further analysis.

Digestion of Sediment Samples

All the reagents used in the analysis were of analytical grade to ensure accurate results. Approximately 1.0g of homogenised sediment was carefully weighed and placed into labelled acid digestion flasks for each sediment sample. Next, specific volumes of reagents were added to each flask, including 10ml of a concentrated acid mixture of HNO_3 (65%), $HClO_4$ (37%), and of H_2SO_4 (30%) (1:2.5:2.5). This process was carried out in a fume chamber to ensure safety. The flasks containing the homogenised sediment samples and reagents were then heated in a block digester (behrotest® K8) at 200 °C for 60 minutes for digestion. After digestion, the samples were cooled in a water bath for 20 minutes within the fume chamber to lower the temperature and release any internal pressure that may have built up. This step also allowed volatilised materials to re-dissolve. The resulting solution was filtered through Whatman No. 42 filter paper into 100ml volumetric flasks. The flasks were then topped up to the mark with distilled water. This procedure was repeated for all samples before the subsequent analysis of AAS (Atomic Absorption Spectroscopy). Reagent blanks and certified reference materials were prepared following a similar protocol to serve as control samples in the analysis process.

3.4.2.3 Sample Preparation and Digestion of MPs

Sample Preparation of MPs

To get rid of any contaminants and silt particles stuck to the surface of the samples, the gathered meso/microplastic samples were washed with purified water. Prior to conducting trace metal analysis, dried plastic particles were measured and weighed.

Acid Digestion of Plastic Samples

Plastic samples of mass 1.0g were weighed into a digestion flask. A volume of 10 ml of concentrated H_2SO_4 was added and allowed to react for 24 hours. After a 24-hour reaction time, 5.0 ml concentrated HNO_3 was added. This was then digested on a block digester (behrotest® K8) for 60 min at 200 °C. The sample was allowed to cool for about 30 min in a fume chamber and diluted to 50 ml with distilled water. The solution was filtered through Whatman No. 42 filter paper into a 100ml volumetric flask and topped to the mark with distilled water. This was repeated for all samples before AAS analysis. Digests were transferred to clean sample tubes and analysed for Lead (Pb), Iron (Fe), Zinc (Zinc), Chromium (Chromium) and Copper (Cu)

3.4.2.4 *Sample Analysis*

Levels of Mercury were determined by Flow Injection Analysis - Atomic Absorption Spectrophotometer (FIA-AAS) (Cold Vapor Technique) using Argon gas as fuel. Levels of Lead (Pb), Iron (Fe), Zinc (Zinc), Chromium (Chromium) and Copper (Cu) were determined using Flame Atomic Absorption Spectrometer (FAAS; Pinnacle 900T) using acetylene gas as fuel and nitrous oxide as oxidant (Chamas *et al.*, 2014).

Acid for digestion plastic and soil samples were introduced into the spectrometer by suction through the AAS nebuliser, and metal concentrations were read and recorded. Analysis of each metal was done in triplicate for each sample, and the mean concentrations were expressed in units of mg/kg as follows:

$$A_s(mg/kg) = \frac{A_d \times V_d}{m_s}$$

Where: A_s = Analyte concentration in sample (mg/kg).

A_d = Analyte concentration acid (mg/L).

V_d = Volume of acid (L).

m_s = mass of sample weighed (kg).

Instrument Parameters and Working Conditions

Tables 3.5 and 3.6 below illustrate the conditions under which AAS analysis was done for each parameter using the AAS.

Table 3. 5: Instrument working conditions for analysing Pb, Fe, Zn, Cr and Cu.

Analyte	Wavelength (nm)	Lamp Current (mA)	Slit width (nm)	Fuel	Oxidant	LOD (ppm)
Pb	283.31	5.1	1.0	C_2H_2	N_2O	0.0004
Cr	357.87	7.2	0.2	C_2H_2	N_2O	0.0008
Cu	324.75	4.1	0.5	C_2H_2	N_2O	0.0015
Zn	213.86	5.2	1.0	C_2H_2	N_2O	0.0007
Fe	248.33	5.0	0.2	C_2H_2	N_2O	0.02

Table 3. 6: Instrument working conditions Hg analysis

Analyte	**Wavelength (nm)**	**Reducing agent**	**Carrier**	**Atomisation temp (^{o}C)**	**Injection volume (µL)**	**LOD (ppb)**
Hg	253.65	0.2% w/v $NaBH_4$ in 0.05% w/v NaOH solution	3 % v/v HCl solution	300	500	0.009

Quality Control

To prevent potential contamination of samples from prior analyses, the glassware utilised in the study was immersed in a solution containing 30% v/v HNO_3 and left to soak overnight. This procedure aimed to ensure the integrity of the subsequent analyses by eliminating any remnants of previous samples. Reagent blanks were prepared the same way as the actual samples to identify and correct any contamination that could arise during the sample preparation process. Standard solutions with known concentrations were also periodically analysed alongside the unknown samples. The percentage metal recovery analysis was conducted for each metal to verify the accuracy of the analytical data. Internal reference materials with known concentrations were used for this purpose. To assess the precision of the analytical data, triplicate measurements were performed for each parameter. The results were then used to determine the relative standard deviation, providing a measure of the precision of the analytical data.

3.4.2.5 Data Analysis

Statistical analyses were conducted using Microsoft Excel 2013 (Microsoft, Redmond, WA, USA) and IBM SPSS version 26. Various statistical tests were employed to assess relationships and differences between datasets. Correlation analysis was conducted to examine the relationships between variables. Descriptive statistics were computed to summarise the data.

Data visualisation techniques were employed to present the results. Statistical significance was considered when $p < 0.05$, indicating a low probability of obtaining the observed results by chance alone.

3.4.2.6 Ecological Risk Analysis of Heavy Metals in Sediments

To evaluate the spatial distribution and heavy metal pollution levels in the study area, pollution indices were calculated. Five environmental indices were employed to assess the risks associated with sediment contamination. Contamination levels and ecological risks were evaluated through the analysis of the ecological risk factor (ER), geo-accumulation index (Igeo), contamination factor (CF), pollution load index (PLI), and ecological risk index (RI) of the sediments.

The Geo-accumulation index (I_{geo}) was utilised to determine the pollution status of heavy metals in river sediments. The calculation of I_{geo} followed Müller's method (1969), which involved comparing the variations between current and preindustrial concentrations of heavy metals. This was achieved using Equation (1)

$$Igeo = log_2\left[\frac{C_n}{(1.5 \times B_n)}\right] \qquad (1)$$

Cn (mg kg^{-1}) represents the concentration of each heavy metal in the sediment sample. On the other hand, the concentration of the corresponding heavy metal in fossil argillaceous silt is represented by Bn (mg kg^{-1}). The Igeo values classify sediments into seven contamination groups, as shown in Table 3.7. According to Müller's (1969) categorization, which is widely used by researchers (e.g., Zhan et al., 2014; Adamu et al., 2015), negative values denote membership in class 0.

According to Cabrera et al. (1999), the Contamination Factor (CF) is the ratio of background concentrations (Cr) to the metal concentrations in impacted areas (Cm). Equation (2) is utilised in its computation:

$$CF = \frac{C_{m}\cdot}{C_r} \qquad (2)$$

This study adopted the baseline values of the WHO/FAO permissible limits for heavy metals in sediments. These limits represent the concentrations of metals above which adverse effects on aquatic organisms are likely or frequently observed. These baseline values are commonly used by various researchers (e.g., Fosu-Mensah *et al*., 2018; Popovici *et al*., 2022). The Contamination Factor (CF) values obtained in our study were classified into six classes, following the classification system proposed by Håkanson (1980) (see Table 3.7).

The analysis employed the Pollution Load Index (PLI), which was created by Tomlinson et al. in 1980. It is computed as the nth root of the product of the values of the contamination factor (CF) and the total of the contamination factors, known as the contamination degree (CD). Equations (3) and (4) show how PLI is calculated.

$$PLI = (CF_1 \text{ x } CF_2 \text{ x } CF_3 \text{ x} \ldots \text{x } CF_n)^{1/n} \qquad (3)$$

n is the quantity of heavy metals that have been measured, and CF is the contamination factor. A qualitative comparison between several sites can be made by the Pollution Load Index (PLI), where PLI<1, PLI=1, or PLI>1 indicate no pollution, baseline pollution levels or indicative of progressive site pollutions respectively.

The Ecological Risk (ER) Factor was determined using Håkanson's (1980) approach to evaluate the ecological risk associated with the identified heavy metals, as indicated by Equation (5):

$$\mathrm{ER} = \mathrm{T_i} \times \mathrm{CF} \qquad (5)$$

According to Håkanson (1980), Ti is the possible ecological risk coefficient of a given heavy metal, CF is the metal contamination factor of each heavy metal, and ER is the ecological risk factor. Pb, Cu, Zn, Cr, and Hg have toxic reaction factors of 5, 5, 1, 2, and 40, in that order. Iron (Fe) having an ER value less than 1 is not taken into account when calculating ER.

Risk index (RI) was used to determine the possible ecological risk posed by each of the metals that were assessed, as per Equation (6): Total Ecological Risk (ER)

$$RI = \sum_{n=1}^{n} ER_n$$

Where n is the total number of detected heavy metal concentrations and $\mathrm{ER_n}$ is the possible ecological risk factor of the nth heavy metal. The RI values are divided into four categories, while the ER values are categorised into five (Table 3.8). High values of ER and RI imply an increased risk for ecosystems.

Table 3. 7: Indices classifications of sediment

Class	**CF Value**[*]	**Quality Class**
1	$CF < 1$	Low
2	$1 \leq CF < 3$	Moderate
3	$3 \leq CF < 6$	Considerable
4	$CF \geq 6$	Very High
	I_{geo} Value[&]	
0	$I_{geo} \leq 0$	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	$5 < I_{geo}$	Extremely Contaminated

[*] Contamination factor (Håkanson, 1980). [&] Geo-accumulation index (Müller, 1969.

Table 3. 8: Hakanson classification for ecological risk (ER) and potential ecological risk index (RI).

ER Class	ER Value	Grades of Ecological risk	RI Value	Grades of Ecological risk
0	ER < 40	Low Risk	RI < 110	Low Risk
1	40 ≤ ER < 80	Moderate Risk	110 ≤ RI <200	Moderate Risk
2	80 ≤ ER <160	Considerable Risk	200 ≤ RI < 400	Considerable Risk
3	160 ≤ ER < 320	High Risk	400 ≤ RI	High Risk
4	320<ER	Very High Risk		

3.4.3 Methods for Social Interactions

3.4.3.1 Research Design

The quantitative approach was used to collect respondents' information to get a general understanding of the research problem. Questionnaire surveys were used to obtain information from respondents on the issues of plastic pollution, and field observations and laboratory work were used to acquire data concerning the microplastic occurrence and interaction with other pollutants in the freshwater environment. The qualitative approach was used to provide an in-depth explanation and understanding of the problem by exploring participants' views. The issues identified and the information gathered from the empirical research concerning plastics management provided insight which guided the design of this research. In addition, this approach allowed for the analyses of the plastics management in the study communities.

The questionnaire survey study employed a descriptive research design. According to Neuman (2000), the design is a scientific methodology that entails monitoring and characterising a subject's behaviour without affecting it. Key (1997) argued that descriptive design aids in learning about the current state of phenomena to describe "what exists" in light of the circumstances or factors involved. The biggest drawback of the descriptive design is ensuring that the survey questions are straightforward, neither inaccurate nor deceptive (Mathers *et al*., 2007).

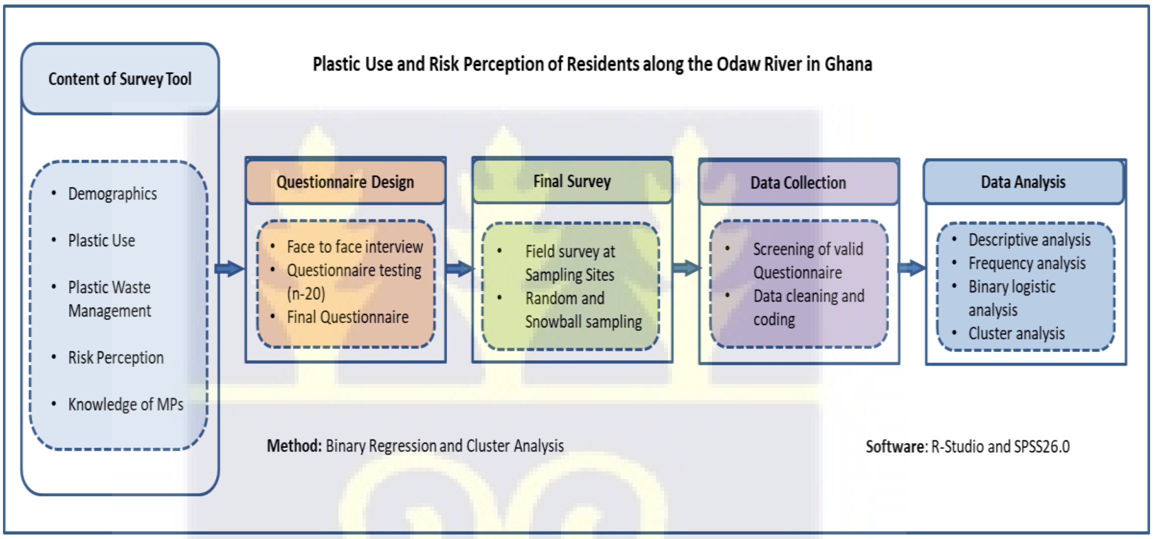


Fig. 3. 6: Flowchart of research methodology and data analysis

3.4.3.1 Sampling and Sample Size Estimation for Surveys

The sample size was computed using the Cochran formula for sample size (Cochran, 1977) at a confidence level of 95% and precision of ±0.5%.

$$n_0 = \frac{z^2pq}{e^2}$$

Where $n_0 = Sample\ size$

$z =$ selected critical value of desired confidence level

$p =$ estimated proportion of an attribute that is present in the population

$q = 1 - p$

$e =$ desired level of precision

To calculate the sample size of the population living along the Odaw River, whose degree of variability is unknown. The maximum variability was assumed, which is equal to 50% (p =0.5) and taking a 95% confidence level with ±5% precision, the calculation for the required sample size is as follows: p = 0.5 and hence q =1-0.5 = 0.5; e = 0.05; z =1.96

This implies,

$$n_0 = \frac{(1.96)^2(0.5)(0.5)}{(0.05)^2} = 384.16 = 384$$

However, in order to have an equal number of samples across the sites chosen, a sample number of 200 was chosen for the sampling zone (upstream, midstream and downstream). Therefore, a sample size (n) of 600 respondents was estimated for the survey.

Participant confidentiality was upheld throughout the study, and explicit consent was obtained before conducting the survey. This study was approved by the Ethics Committee for Basic and Applied Sciences (ECBAS) of the University of Ghana with an approval number of ECBAS066/21-21 (Appendix 2).

Out of the total sample size of 600, all 600 respondents willingly agreed to take part in the survey. The survey was conducted using a combination of tablet computers and printed paper, with a digital coding system implemented for data organisation. It followed a structured format, covering various significant aspects such as plastic consumption, plastic waste management, perception of plastic-related risks, and knowledge regarding microplastics (MPs).

3.4.3.2 Sampling Approach

A cluster random approach was used for the target sample populations. Four towns were chosen to represent upstream, midstream and downstream settlements of the Odaw River. The rationale behind this was: (1) urban districts have the most significant absolute number of plastic users; (2) along the Odaw River, plastic waste contamination is easily visible and has a substantial negative influence on the ecosystem and human health (Ntajal *et al.*, 2022). Random walks were used to approach individual homes. Three study teams randomly selected different routes and stopped at each suitable home along the way to conduct surveys. (Aleksandr Makarchev, 2022). Face-to-face survey procedures are used in conjunction with random and snowball sampling approaches.

3.4.3.3 Data Collection

Questionnaire Design and Testing

The assessment of factors such as behavioral intentions toward plastic consumption, environmental knowledge, attitudes, and subjective norms related to plastic waste concerns underwent a thorough examination, drawing insights from established theories and prior research. Additional items were formulated to create a comprehensive questionnaire tailored for the purposes of this study.

Prior to being distributed to the target group (residents of Old Fadama, Christian Village, Haatso, and Brekusu), the questionnaire underwent a pilot test to ensure maximum clarity, appropriateness, and consistency of interpretation. Twelve people from the University of Ghana Campus participated in the experiment. They were primarily on-campus residents. This pilot research was also used to teach enumerators how to get participants involved in distributing the questionnaire. In this procedure, five enumerators received training. Afterwards, various modifications were made regarding the wording and phrasing, question sequencing, and complexity (Choi and Pak, 2005). The resulting survey questionnaire contained (1) 28 questions, (2) five logically advancing sections (i.e., socio-demographic, consumption behaviour, plastic waste management, risk perception, and MPs knowledge) (Appendix 1). The questionnaire included data on socio-demographic factors such as age, sex, level of education, monthly income and occupation, (3) contextually appropriate questions, and (4) unambiguous questions, each addressing one concept. (Makarchev *et al.*, 2022).

Questionnaire Administration

Data collection took place between August 28 and September 6, 2022, using digital software Kobo Toolbox (The International Rescue Committee (IRC), Harvard Humanitarian Initiative (HH), and the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) jointly developed the Kobo Toolbox) a user-friendly and reliable digital data collection tool, for humanitarian use. Data were collected face-to-face. Due to Ghana's poor and occasionally nonexistent internet access, its capacity to be deployed online and offline makes it the ideal data collection mask for the country's environment. Five field enumerators, together with a few chosen community leaders, assisted in gathering the data.

All of the enumerators had bachelor's degrees and were familiar with the study communities, were fluent in some of the native languages spoken and had expertise collecting data using the Kobo Toolbox or digital platforms for collecting social data. Enumerators were trained and introduced to the data collection protocols and tools, proper translations, and using the Kobo Toolbox. Throughout the data collection period, 600 questionnaires were distributed. To ensure data integrity uncompleted questionnaire and questionnaires which had distorted messages or could not be properly read were omitted (Xu *et al*., 2022). After data was cleaned and questionnaires with omissions and apparent errors deleted, 583 valid questionnaires (residents) were obtained, with 97.16% effective rate**.**

3.4.3.4 *Structural Equation Modelling*

To assess the relationship between the factors studied, the following assumptions were made and tested with SEM;

- *Risk perception has a positive association with plastic use behaviour*
- *Knowledge of MPs as a positive association with Plastic Use behaviour*
- *Risk perception has a positive association with Plastic waste management*
- *There is a positive association between MPs Knowledge and Risk* perception.

Confirmatory factor analysis (CFA) evaluates a measurement model's dependability. Prior to the analysis, CFA enables the researcher to instruct the SEM programme on which variable belongs to which factor. Using CFA, the researcher can describe the relationships and connections between the variables. The degree to which a group of measured items genuinely represents the theoretical latent construct that those items are intended to test is known as construct validity. The dependability of the variable value scale was investigated by establishing a CFA model using the AMOS software version 26 (IBM. SPSS)

After determining whether a scale is appropriate for measuring the various research variables, the following stage is to test the linkages in a structural model that has been theorised. Four factors (Latent variables) were investigated in this study, with three observed variables associated with each latent variable. The relationship model variable is a new relationship between variables that have not been introduced.

3.4.3.5 Data Analysis

Data was imported from the Kobo Toolbox directly into MS Excel and cleaned for further analysis. Statistical analysis was done using R-Studio (Open-source statistical software: https://www.r-project.org/) and SPSS version 26. Descriptive statistics, which included calculating percentages, standard deviations, and mean values were conducted. Tables and bar graphs were also used to illustrate the survey data. Moreover, the R "psych" package was used to analyse the "qualitative" variable data (Nguyen *et al*., 2022)

Logistic Regression Model techniques can be used to evaluate and comprehend intricate variable connections. In order to determine how demographic characteristics, notably gender, age, education, income, and occupation, affect respondents' use of plastic, a binary logistic regression model was used. Notably, the respondents were required to choose between two alternatives when indicating their behaviour regarding plastic usage: 0- indicating the affirmative choice and 1- representing the negative choice. As a result, these dependent variables in the regression model were considered noncontinuous. Either logistic regression or probit regression when the dependent variable is in the 0–1 style. If the decision on how to respond is based on maximising utility, then some academics believe that the logistic model is a superior option. The logistic model was chosen for this study since the influencing factors primarily determine how respondents' behaviour changes regarding their use of plastic.. (Xu *et al*., 2022). To check for significance, t-tests were also used to analyse the plastics management data. The results of the statistical analysis were interpreted as significant when reaching this threshold.

Additionally, the social data on plastics use and behaviour were analysed using three statistical methods: the Chi-square test of independence, the Kruskal Wallis rank sum test, and the two-step clustering procedure. The respondents were divided into groups according to their log-likelihood distance measure and Schwarz Bayesian Criterion (BIC) using a two-step clustering procedure based on their behaviour in plastic use. The two-step clustering technique was appropriate because, in contrast to other conventional clustering techniques, it may be used to cluster both continuous and categorical variables (Bacher et al., 2002). Additionally, it aids in resolving the issue with cluster algorithms related to a few clustering methods, including the agglomerative hierarchical clustering method and the k-means cluster (Bacher, 2000). Furthermore, the log-likelihood estimation, which determines the likelihood of cluster membership dependency, and the two-step clustering technique, was used to analyse respondents' socio-demographic characteristics to understand the clusters' identities to enable the targeting of attitudinal and behavioural interventions towards reducing plastics in aquatic pollution. (Adam *et al*., 2021). This helps to identify natural categories in a dataset that might not be apparent otherwise because it is based on one or more probability distributions (Bacher, 2000; Pallant and Manual, 2010).

CHAPTER FOUR

RESULTS

4.1 Background

In this chapter, the principal findings of the study are presented. These findings have been systematically categorized into three distinct domains, each aligned with the specific objectives of the study: Occurrence, Interaction with heavy Metals, and Social Interactions. Commencing with an in-depth examination of the presence and characteristics of microplastics within the Odaw River (Occurrence). The chapter subsequently delve into the results and analysis of the interplay between heavy metals, microplastics, and sediments (Interactions). Finally, the chapter culminates with a thorough examination of the socio-environmental aspects, encompassing the interactions and implications of plastic usage within the communities situated along the Odaw River (Social Interactions). This chapter offers a comprehensive overview of this study's primary outcomes, providing a foundation for the subsequent chapters' in-depth discussion.

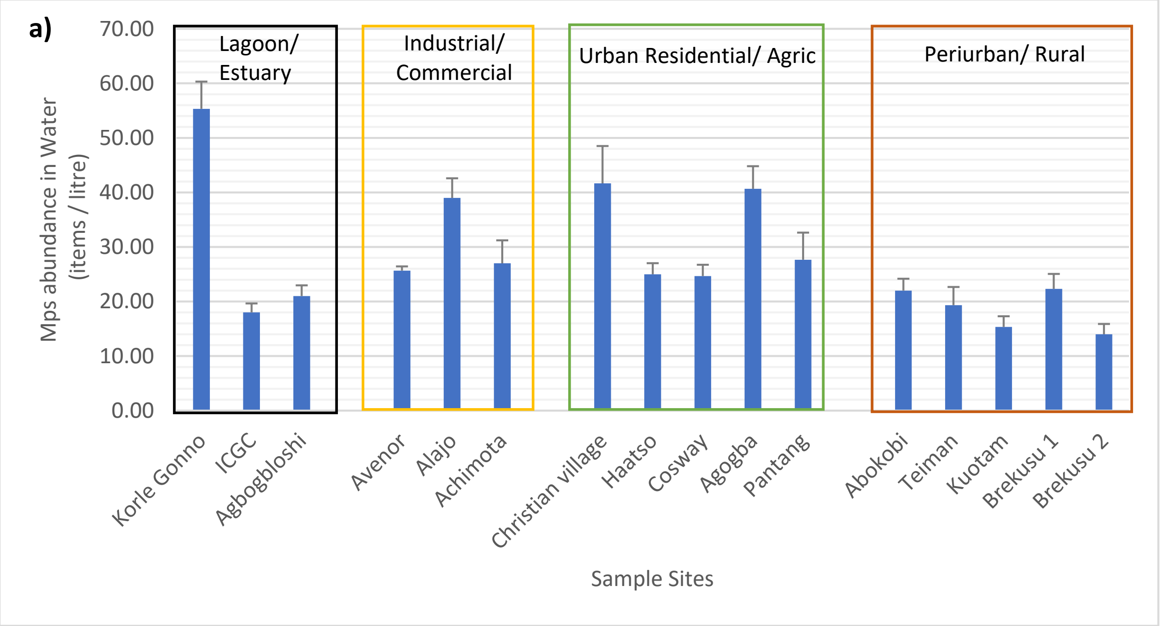
4.2 Occurrence Microplastics in Odaw River

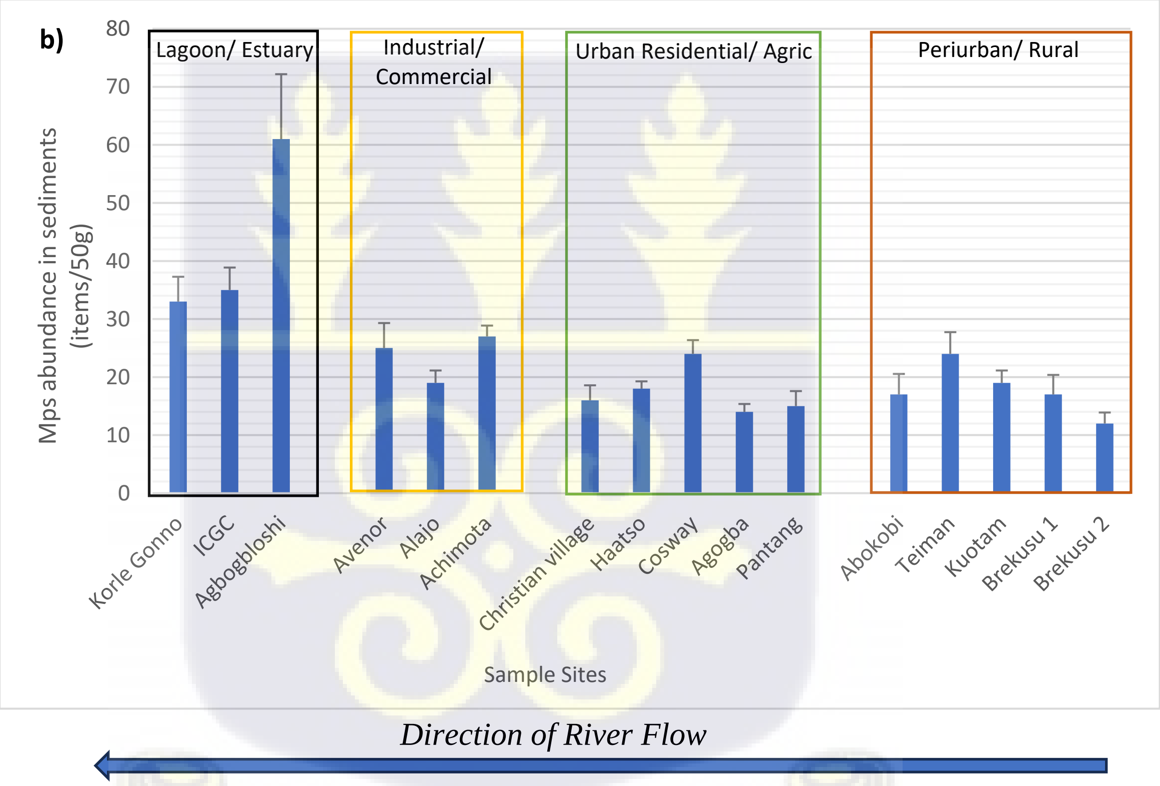
4.2.1 Abundance and Spatiotemporal Distribution of MPs

4.2.1.1 Spatial Distribution

Microplastic particles were detected in the water (Fig. 4.1a) and sediment (Fig. 4.1b) of all sampling sites along the Odaw River. Although water samples generally recorded higher concentrations of MPs than sediments samples, the was no significant difference ($p > 0.05$) in the abundance of MPs in both media (water/ sediments). Microplastic abundance in water and sediment ranged between 14-56 items/l and 12-60 items/50g, respectively (Fig 4.1). The average concentration of microplastics was 27.44 ± 11.25 items/l in surface water and 23.50 ± 11.97 items/50g in sediment. Microplastic accumulation in water and sediments significantly differed among sampling sites ($p < 0.05$). The highest abundance in MPs in surface water was located at Korle Gonno (Estuary) (55.33 items/l), and that for sediments was at Agbogbloshie (61.00 ±11.17 items/ 50g) (Fig. 4.1). The lowest concentrations of MPs were recorded at the source of the Odaw River in Brekusu (Brekusu 2) (14.00 ± 1.89 items/l; 12.00 ± 1.90 items/50g) in water and sediment samples, respectively.

The river was categorised into four zones; Lagoon/Estuary zone, Industrial/ Commercial zone, Urban residential/ Agriculture zone and Periurban/ Rural zone. There were variations in the abundance of microplastics between the four types of zones; the periurban and rural zone (upstream) recorded relatively low average concentrations per litre for water samples (18.60 ± 4.48 items/l), and for sediment samples, the lowest concentrations were in the urban residential and agriculture (midstream) zone (17.40 ± 4.00 items/50g). The highest average concentrations of MPs in water samples were at urban residential and agriculture (midstream) zone (31.93 ± 8.50 items/l). However, the highest absolute concentration was at the estuary (Korle Gonno) and Agbogbloshie for water and sediments, respectively. Furthermore, the highest MP concentrations in sediment were downstream (industrial/ commercial zone and Lagoon/ Estuary). Microplastic particles in sediment were more abundant downstream of the river, while surface water contained more microplastics midstream (Table 4.1). ANOVA revealed there is no statistically significant differences in MP abundance between zones (Kruskal-Wallis's test, P=0.198).





The direction of sites is from the downstream at the Korle estuary to Upstream in Brekusu. The sampling field has been classified into four zones: Lagoon and Estuary, Industrial/ Commercial, Urban Residential and Agriculture, and Periurban and Rural. Standard deviation of three replicates is represented by error bars

Fig. 4. 1: Average abundance and distribution of MPs (items/l) in surface water (a) and (items/50g) in sediments (b) at 16 sampling sites in the Odaw River basin.

Table 4. 1: Average abundance of MPs (water and sediments) in land use zones and up, mid and downstream regions of the Odaw River

Region	Land use Category	Water (items/l)	Sediment (items/50g)
Downstream	Lagoon/ Estuary	31.44 ± 20.74	43.00 ±15.6
	Industrial/ Commercial	30.56 ± 7.34	23.67 ± 4.2
Midstream	Urban Residential/ Agriculture	31.93 ± 8.50	17.4 ± 4.0
Upstream	Periurban/ Rural	18.60 ± 4.48	17.8 ± 4.3

4.2.1.2 Temporal Distribution

The seasonal variation in microplastic (MPs) concentrations in both sediments and water was more pronounced during the wet season, compared to the dry season. In contrast, the dry season exhibited relatively lower MPs concentrations in the water, although no significant difference ($p>0.05$) was found between the two seasons (as shown in Fig. 4.2 a and b, and Fig. 4.3 a and b). Notably, there was a noticeable increase in MPs concentrations in sediments during the wet season compared to the dry season, as depicted in Fig. 4.2b and Fig. 4.3b.

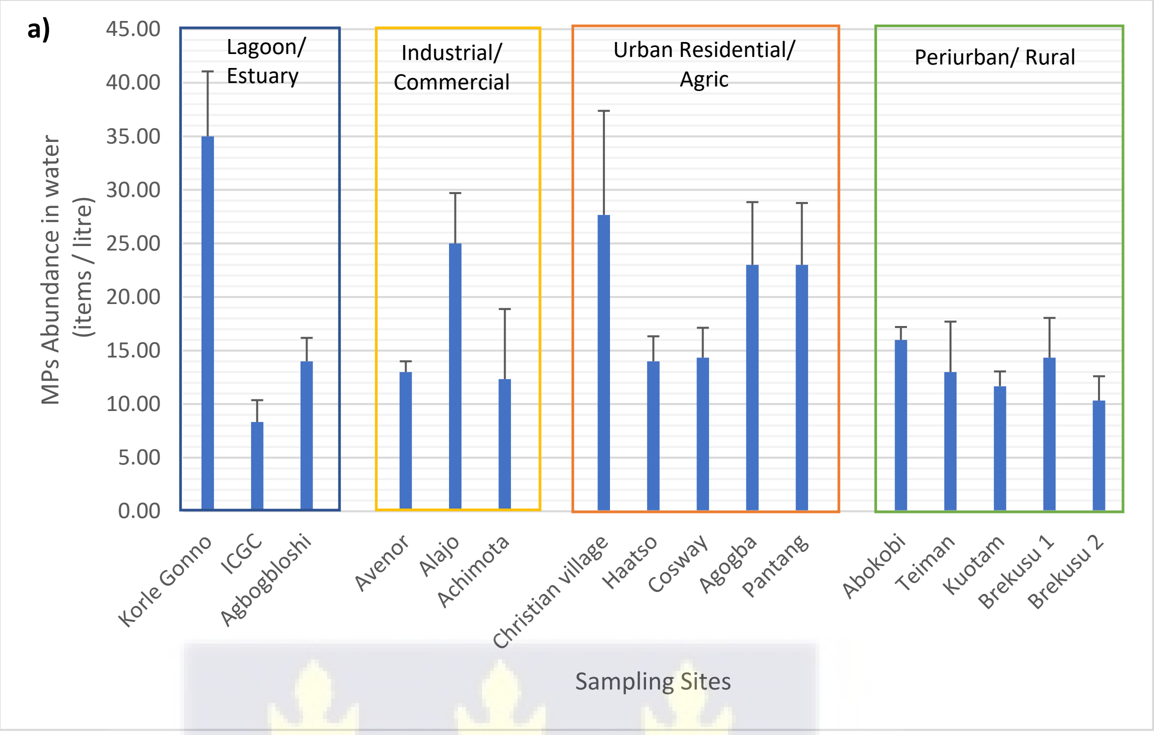
In both wet and dry season, concentration of MPs in water was highest at Korle Gonno (Estuary) (35.00 ± 6.06 items/l and 20.33 ± 2.71 items/l) respectively (Fig. 4.2a and Fig. 4.3a), whiles the lowest MPs content was recorded at ICGC (8.33 ± 2.03 items/l) (Fig. 4.3a) in the wet season and Brekusu 2 (Source) (3.67 ± 0.19 items/l) (Fig. 4.3a) in the dry season. On average, the industrial/commercial zone (13.78 ± 1.02 items/l) and the Urban Residential and Agriculture zones (20.40 ± 6.00 items/l) (midstream) recorded the highest concentrations of MPs in water (Table 4.2). Periurban and Rural zone recorded 13.07 ± 2.22 items/l in the wet season and; 5.53 ± 1.86 items/l in the dry season in water. These were the lowest concentration of MPs in water in both seasons (Fig. 5.3a and Fig. 5.4a).

Sediments samples had the highest concentrations of MPs in Agbogbloshie (47.00 ± 12.50 items/50g) in the wet season (Fig. 4.2b) and at Korle Gonno (Estuary) (20.00 ± 4.16 items/50g) in the dry season (Fig. 4.3b). Agbogba (5.00 ± 0.58 items/50g) and Abokobi (1.00 ± 0.58 items/50g) recorded the lowest concentration in the wet and dry seasons, respectively (Fig 4.2b and Fig. 4.3b). The Lagoon/ Estuary zone (downstream) (Fig 4.2b and Fig. 4.3b) recorded the highest concentrations in the wet season (28 ± 17.35 items/50g) and dry season (15.00 ± 4.58 items/50g). In the wet season, the urban residential and agriculture zones (11.00 ± 3.74 items/50g) recorded the lowest concentrations of MPs in sediments. Whiles in the dry season, the industrial/ commercial (6.33 ± 4.04 items/50g), urban residential/ agriculture (6.40 ± 3.21 items/50g) and periurban/ rural (5.40 ± 4.34 items/50g) recorded the lowest concentrations (Table 4.2).

Table 4. 2: Seasonal Abundance (Water, Sediments) of MPs in Land Use Zones and Up, mid and Downstream Regions of the Odaw River

		Wet Season		Dry Season	
Region	**Land use Category**	**Water (items/l)**	**Sediment (items/50g)**	**Water (items/l)**	**Sediment (items/50g)**
Downstream	Lagoon/ Estuary	19.11 ± 14.05	28 ± 17.3	12.33 ± 7.06	15.00 ± 4.58
	Industrial/ Commercial	16.78 ± 7.13	17.33 ± 3.21	13.78 ± 1.02	6.33 ± 4.04
Midstream	Urban Residential/ Agriculture	20.40 ± 6.00	11.00 ± 3.74	11.53 ± 4.81	6.40 ± 3.21
Upstream	Periurban/ Rural	13.07 ± 2.22	12.40 ± 2.88	5.53 ± 1.86	5.40 ± 4.34

Wet Season



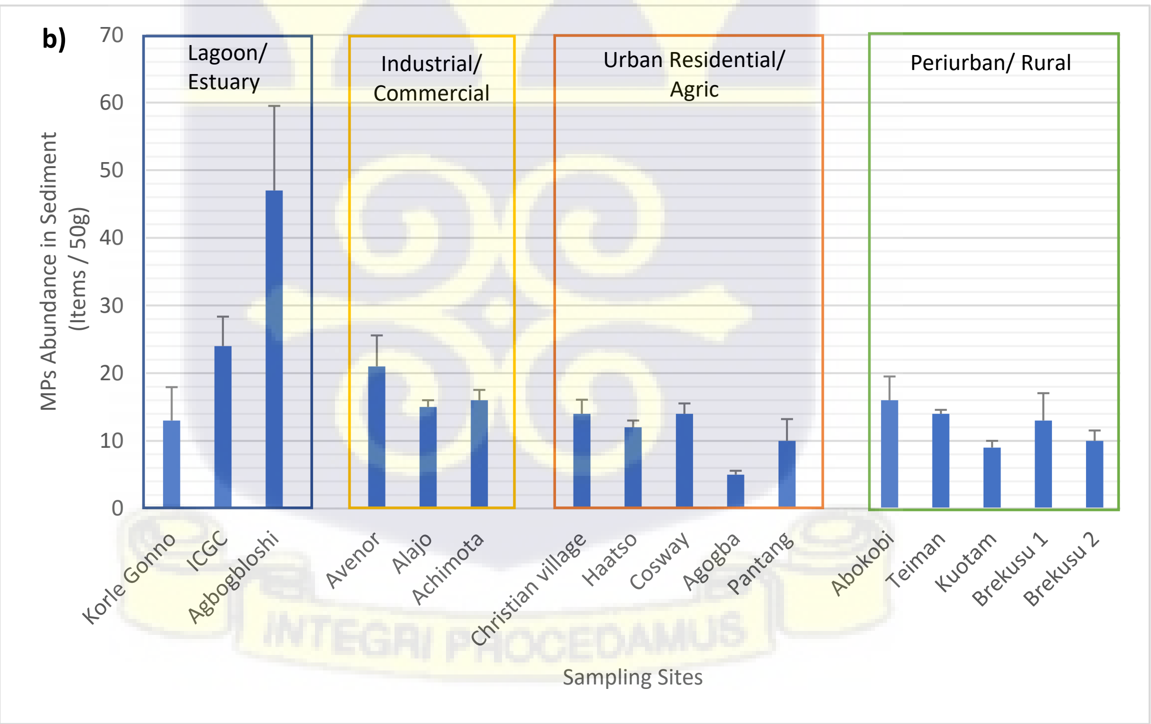
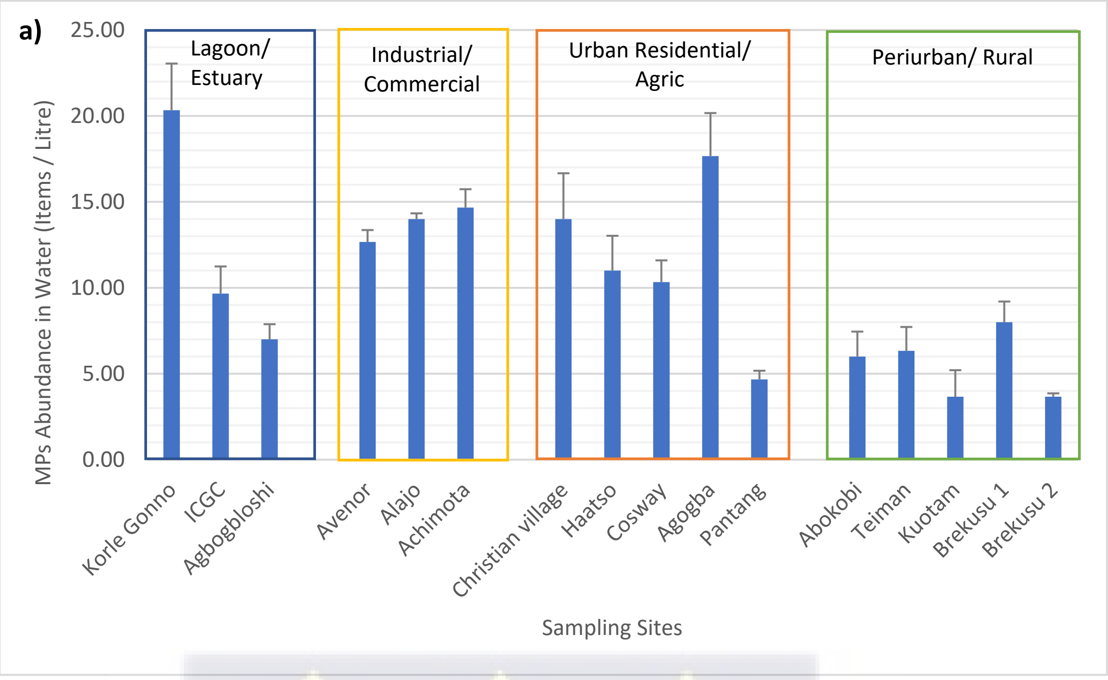


Fig. 4. 2: Abundance and spatial distribution of microplastics in (a) surface water (items/l) and (b) sediment (items/50g) in the wet season in the Odaw River.

Dry Season



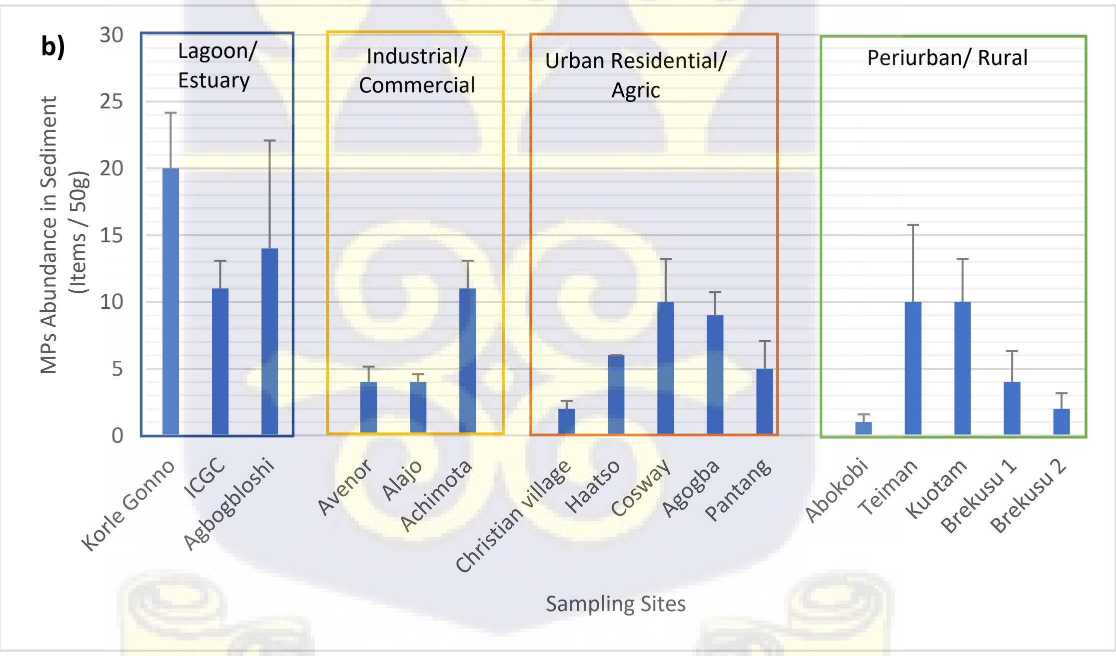


Fig. 4. 3: Abundance and Spatial distribution of microplastics in (a) surface water (items/l) and (b) sediment (items/50g) in the dry season in the Odaw River.

4.2.2 Morphological Characteristics of MPs (Shape, Size and Colour)

Fibers were the most prevalent microplastic shapes, accounting for 73.4% of the total, followed by film (18.7%) and fragments (7.4%) in water samples. Pellets were the least common, comprising only 0.5% of the microplastics found in water samples, and beads were entirely absent. In sediment samples, fibers remained prominent at 42.6%, followed by fragments at 32.2%, and film at 24.7%. There were no pellets found in the sediment samples. A higher fibre percentage was in water, 73.4%, than in sediment, 42.6%. While sediments contained a greater abundance of fragment shapes (32.2%) than water samples (7.4%) (Table 4.3) and Fig 4.5a, b). All sites recorded higher concentrations of fibre particles than other forms of MPs. Fig. 4.4 shows the pictures of observed shapes using the stereomicroscope.

Microplastic samples ranged from <50 – >5000 µm in size. MPs samples with sizes between 1000-3000 µm were the most abundant (water: 45.0% and sediments: 46.7%), followed by sizes between 500-1000 µm (water: 30.3% and sediments: 34.5%). In water samples, microplastics were observed in relatively smaller sizes and in limited quantities, but they were entirely absent in sediment samples. with sizes below 50 -200 µm. There was no significant difference (p>0.05) in the sizes of MPs in water and sediments observed at all sites. (Fig. 4.5c, d) (Table 4.3).

Several microplastic colours were observed; colours were grouped into seven colours; black, white, red, blue, yellow, transparent and others. The dominant colour of microplastics was black (water: 66.7%, sediments: 47.6%) at all sampling sites, followed by transparent (water: 14.4%, sediments: 11.6%), red (10.6%) in water and others (10.8%) for sediments. More colours were observed in sediment samples than in water samples (Fig. 4.5 e, f) (Table 4.3).

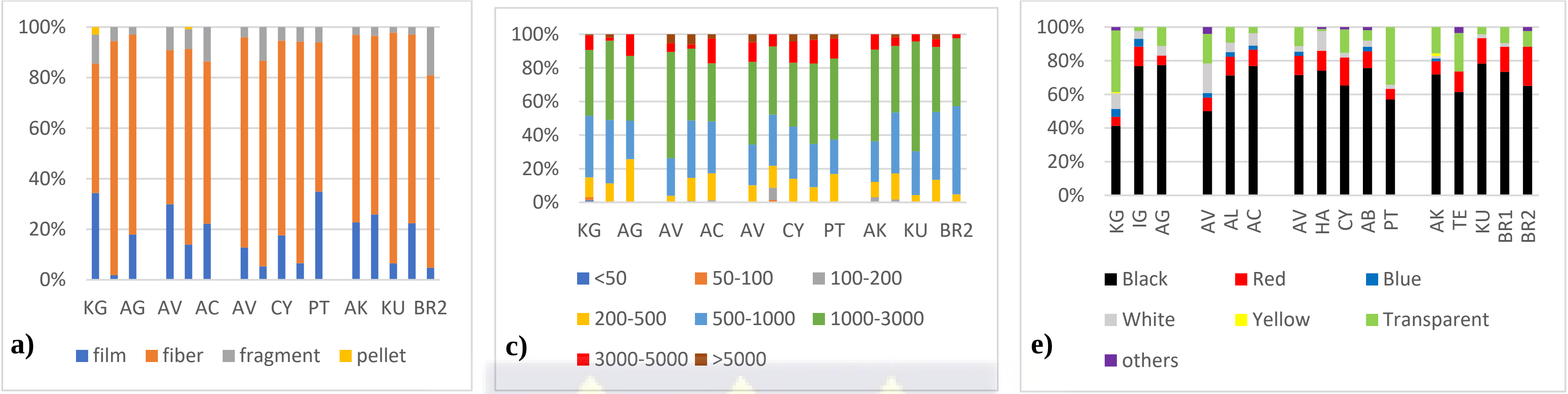
Table 4. 3: Percentage Abundance of MPs Morphological Characteristics in water and sediments

Characteristics	**Percentage**	
Shapes	**Water**	**Sediments**
Fibre	73.4	42.6
Film	18.7	24.7
Fragment	7.4	32.2
Beads	-	0.5
Pellets	0.5	-
Sizes (µm)		
<50	0.2	-
50-100	0.3	-
100-200	0.8	0.3
200-500	12.2	8.0
500-1000	30.3	34.5
1000-3000	45.0	46.7
3000-5000	8.7	6.6
>5000	2.5	4.0
Colour		
Black	66.7	47.6
Red	10.6	8.6
Blue	1.8	6.5
White	5.5	12.2
Yellow	0.2	2.7
Transparent	14.4	11.6
Others	1.0	10.8

Bead **Fibre** **Fragment** **Film**

Fig. 4. 4: Images from microscopic observations of MPs form/shapes of samples

Water Samples



Sediments Samples

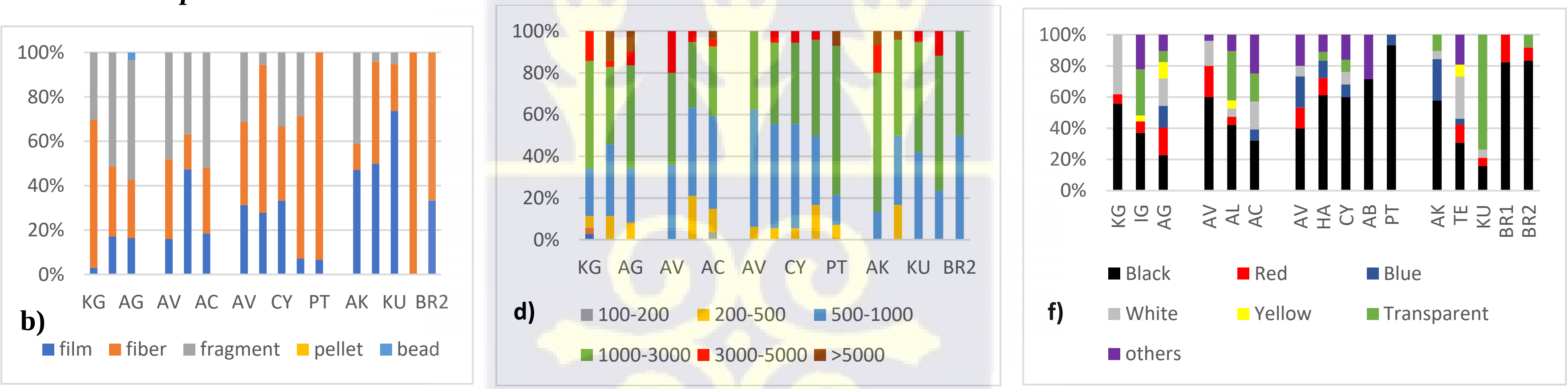


Fig. 4. 5: Shape (**a, b**), Size (µm) (**c, d**) and Colour (**e, f**) distribution as a per cent of the total number of MPs present in the samples of a) surface water (items/L) and b) sediments (items/50g), respectively, taken from 16 sampling sites (including four zones, i.e., Lagoon and Estuary area, industrial/ commercial area, Urban residential and agriculture and the periurban and rural).

4.2.3 Plastics Polymer Composition

Identified MPs Polymeric Proportion

Randomly selected MPs from water and sediment samples and polymers were identified using FTIR. Polymers were classified into polypropylene (PP), polyethylene (PE), polystyrene (PS), polyester and others (Fig. 4.6). Polyethylene was the most common polymer (48% of all particles), followed by PP (19%), PS (11%), Others (13%) at all sampling sites and within environmental media (water and sediment). Fig. 4.7 illustrates the spectral image of polymers observed (PE, PP, PS and Polyester).

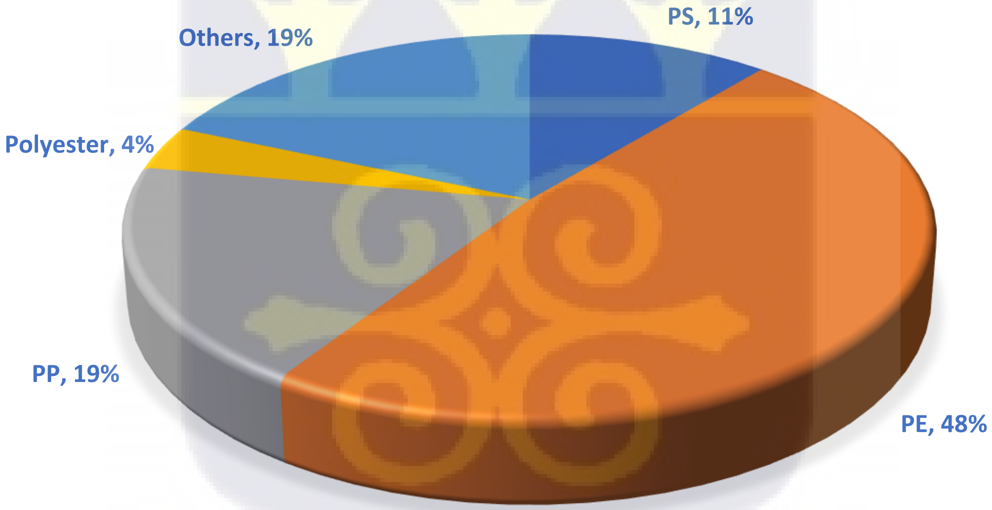
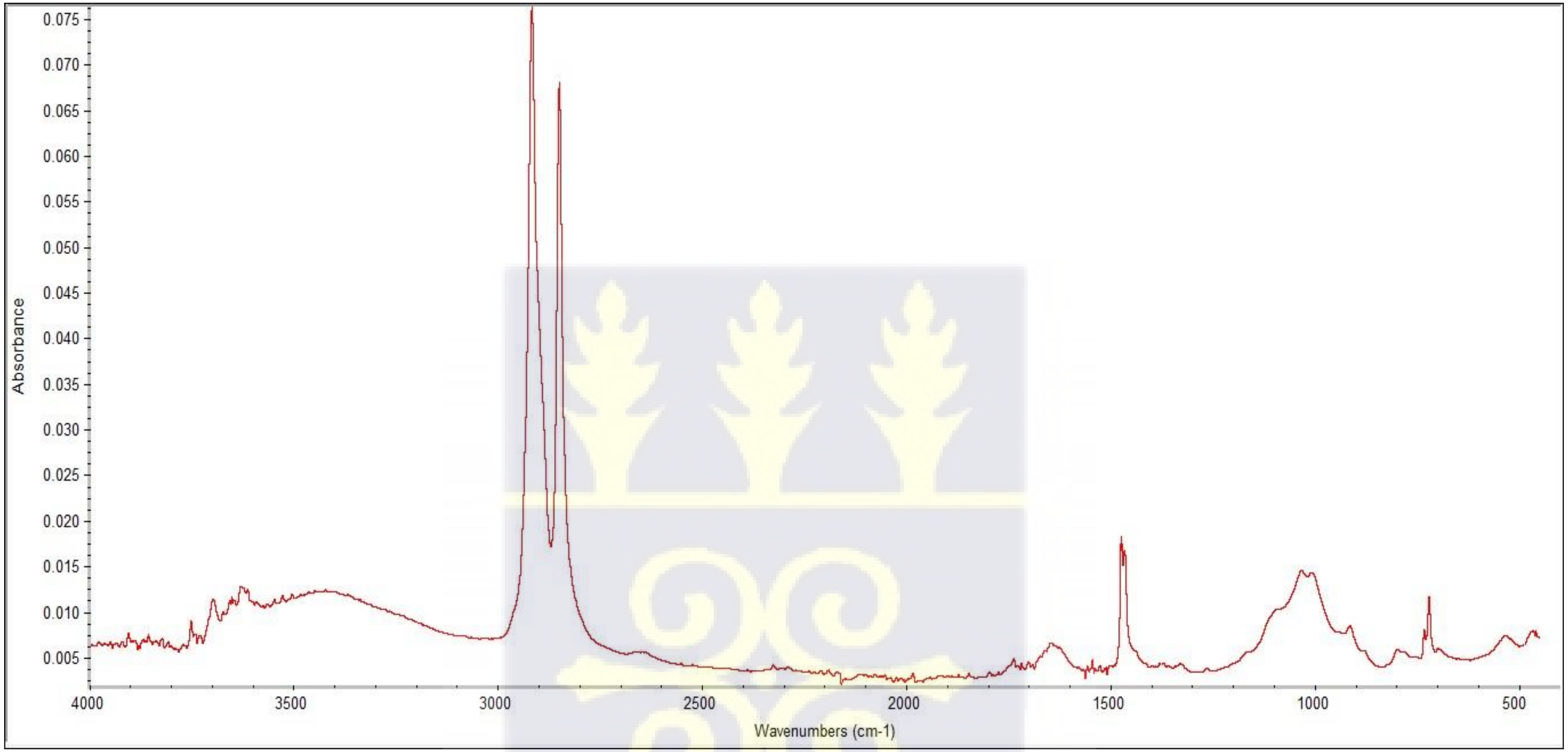
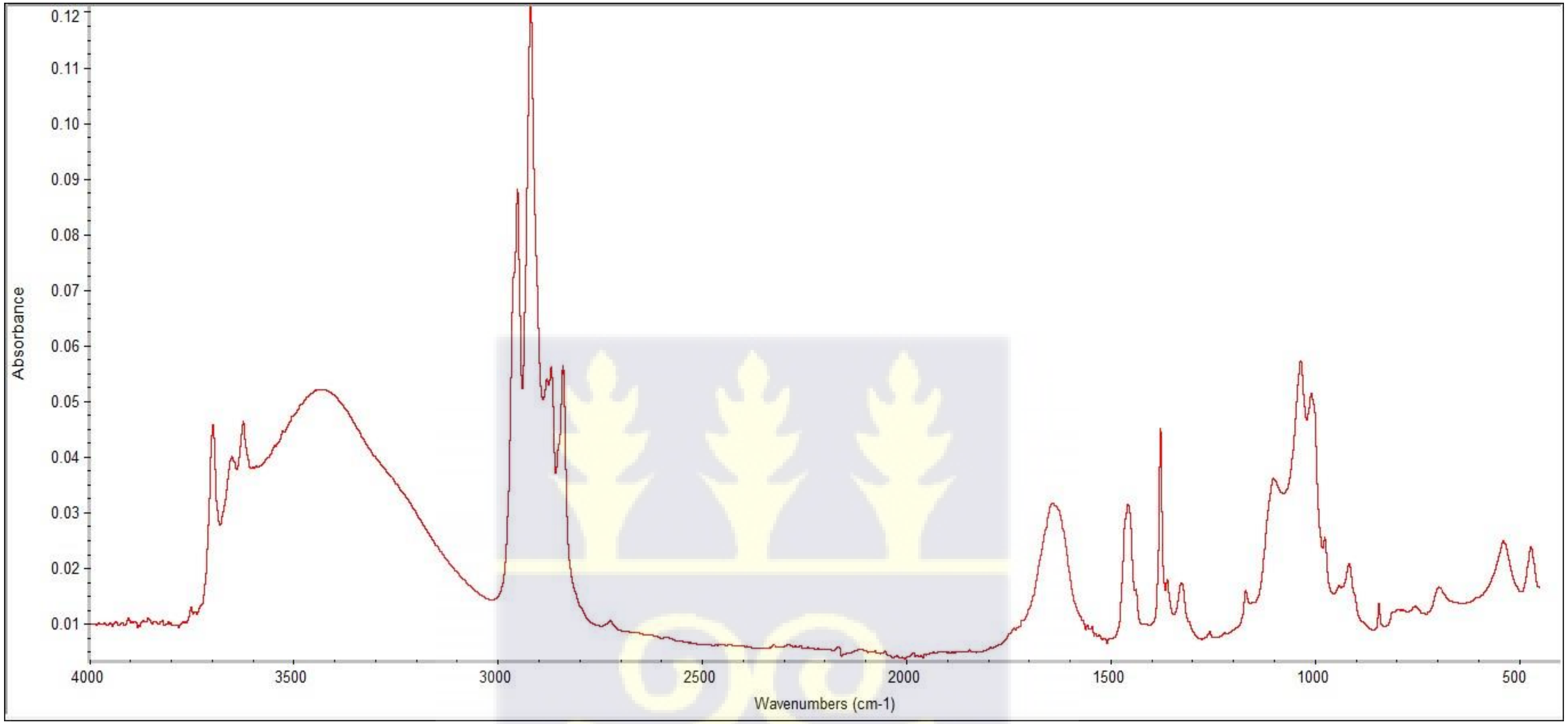


Fig. 4. 6: Polymer identification of samples collected from Odaw River. PE, Polyethylene, PS, Polystyrene, PP, Polypropylene. (**Sample number=27**)

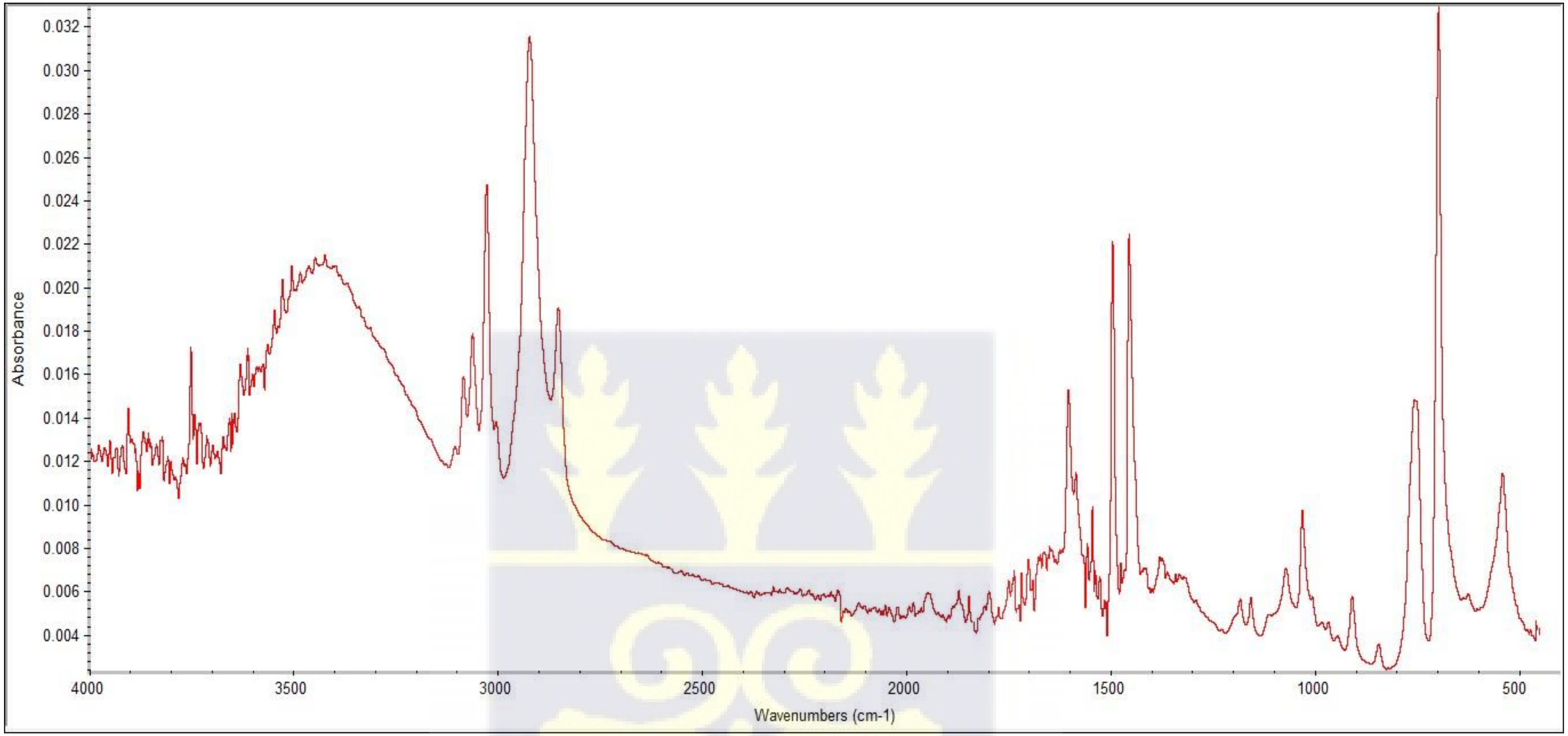
Polymer Spectral Analysis



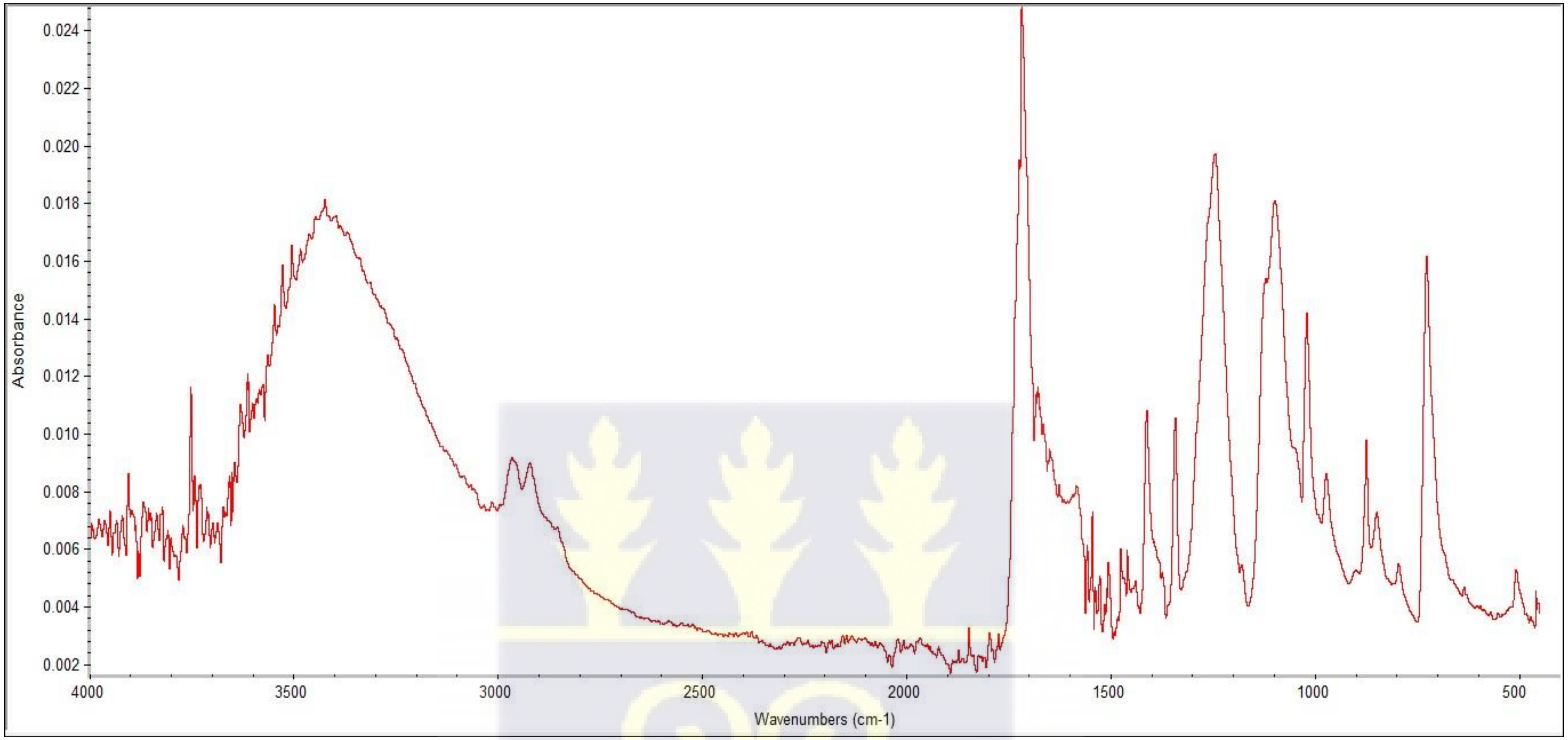
a) Polyethylene (PE)



b) Polypropylene (PP)



c) Polystyrene (PS)



d)Polyester (PES)

Fig. 4. 7: FTIR spectra of Microplastic showing polymer types; (a) polyethylene (PE), (b) polypropylene (PP) (c) polystyrene (PS) and d) Polyester (PES)

4.2.4 MPs Risk Assessment

The pollution load index (PLI) was calculated based on microplastic concentration at the various sampling sites. Variations in the pollution load index in the Odaw River samples were categorised into four levels, including low, moderate, high and extremely high pollution (Table 3.4). The PLI of surface water and sediments showed predominantly high levels of microplastic pollution, PLI= >30 (IV= extremely high pollution) in the wet season. Water samples revealed that Korle Gonno (PLI=59.16), Alajo (PLI=50.00) and Christian Village (PLI=52.60) had extremely high levels of MPs pollution (IV) during the wet season, additionally, extremely high levels were recorded at Agbogbloshie in sediments (PLI = 68.56) during the wet season (Table 4.5). Microplastic pollution in surface water showed moderate levels (PLI = 10-20), while sediments had high levels (PLI = 20-30), with some sites downstream showing extremely high levels in the dry season. The lowest PLI score was recorded at Abokobi in sediments in the dry season. Microplastic pollution in surface water and sediments sampled during the wet season was higher when compared to the dry season. PLI zone was extremely high (PLI=>30) in all zones in the wet season; thus, the Odaw River is highly polluted with MPs in the wet season. In the dry season, the Periurban/ rural zone recorded moderate pollution in water samples. Sediments samples also had high pollution levels at all sites except the Periurban zone, which had moderate pollution levels of MPs (Table 4.5).

Four main polymers were recorded in the Odaw River, polystyrene, polypropylene, polyethylene and polyester. Of these, the most abundant was polyethylene. The polymer hazard index (H) values in the Odaw River by the random selection of polymers from sites was H=1355, a risk level criterion of IV (extremely high). The highest polymer hazard score in the Odaw River was Polyester (score 1117) (Table 4.4).

Table 4. 4: Polymer Risk Index (H) of sampled polymers in the Odaw River

Polymer	**Pn**	**Sn**	**H**	**Risk Level Criteria**	
PS	3	30	90	II	Moderate Pollution
PE	13	11	143	III	High Pollution
PP	5	1	5	I	Low Pollution
Polyester	1	1117	1117	IV	Extremely high Pollution
Others *	5	-	-	-	-
Total Hazard Score			**1355**	**IV**	**Extremely high Pollution**

*Other polymers were Cellophane which recorded a very low (<50%) match during FTIR spectrum analysis. There are also no Sn values for Cellophane.

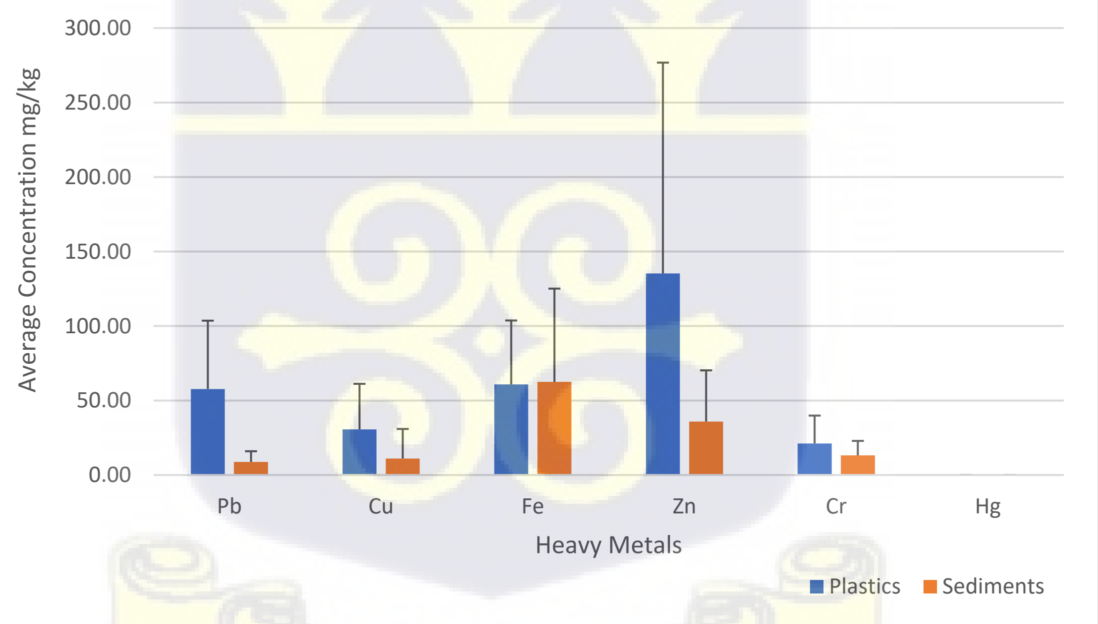
H= Polymer Risk Index, Pn= frequency of polymers, Sn= Hazard Score of Polymer

Table 4. 5: Risk level criteria of microplastics in the Odaw River during wet and dry seasons based on Pollution Load Index (PLI) score for Sampling sites and zone.

		Wet Season				**Dry Season**			
Lagoon/ Estuary	Sites	**Water**	**Score**	**Sediments**	**Score**	**Water**	**Score**	**Sediment**	**Score**
	KG	59.16	IV	36.06	IV	45.09	IV	44.72	IV
	IG	28.87	III	48.99	IV	31.09	IV	33.17	IV
	AG	37.42	IV	68.56	IV	26.46	III	37.42	IV
	PLIzone	**39.98**	**IV**	**49.47**	**IV**	**33.35**	**IV**	**38.14**	**IV**
Industrial/ Commercial	AV	36.06	IV	45.83	IV	35.59	IV	20.00	II
	AL	50.00	IV	38.73	IV	37.42	IV	20.00	II
	AC	35.12	IV	40.00	IV	38.30	IV	33.17	IV
	PLIzone	**39.86**	**IV**	**41.41**	**IV**	**37.08**	**IV**	**23.67**	**III**
Urban Residential/ Agriculture	CV	52.60	IV	37.42	IV	37.42	IV	14.14	II
	HA	37.42	IV	34.64	IV	33.17	IV	24.49	III
	CY	37.86	IV	37.42	IV	32.15	IV	31.62	IV
	AB	47.96	IV	22.36	III	42.03	IV	30.00	III
	PT	47.96	IV	31.62	IV	21.60	III	22.36	III
	PLIzone	**44.34**	**IV**	**32.14**	**IV**	**32.49**	**IV**	**23.62**	**III**
Periurban/ Rural	AK	40.00	IV	40.00	IV	24.49	III	10.00	II
	TE	36.06	IV	37.42	IV	25.17	III	31.62	IV
	KU	34.16	IV	30.00	IV	19.15	II	31.62	IV
	BR1	37.86	IV	36.06	IV	28.28	III	20.00	II
	BR2	32.15	IV	31.62	IV	19.15	II	14.14	II
	PLIzone	**35.94**	**IV**	**34.82**	**IV**	**22.97**	**III**	**19.51**	**II**

4.3 Interactions of Heavy Metals, Microplastics and Sediments

The concentrations of all target metals were measured both in meso/microplastics (MMPs) and sediments at each sampling site, and the results are presented in Fig. 4.8. Iron (Fe) was the most recorded at all sites, and Hg was the least recorded. Hg was not detected at some sites, as the reading may have fallen below the detection limit. The mean concentration of Pb, Cu, Fe, Zn, Cr and Hg recorded in meso/microplastics particles was 57.73 mg/kg, 30.63 mg/kg, 6079.22 mg/kg, 135.25 mg/kg, 21.14 mg/kg and 0.05 mg/kg, respectively, while the mean concentration of Pb, Cu, Fe, Zn, Cr and Hg in sediments were 8.764 mg/kg, 11.09 mg/kg, 6248.55 mg/kg, 35.83 mg/kg, 13.17 mg/kg and 0.02 mg/kg, respectively. The total mean concentration of target metals in the MP particles were greater than those in the soils for all elements except Fe (Fig 6.2).



*For purposes of the graph, all elements were measured in mgkg^{-1} except for Iron which had the mean percentage because of the high values recorded.

Fig. 4. 8: Average concentrations of heavy metals in meso/microplastics and sediments

Agbogbloshie had the highest concentration for all elements for the distribution of heavy metals in sediments and MMPs along the Odaw River (Table 4.6). No records were taken for heavy metals in plastics for Brekusu Source (BS) since no plastics were found in the sediments. On average, concentrations of Fe and Hg were higher in sediments than in MMPs for all sites (Fig. 4.9). Other Heavy metals (Cr, Cu, Zn and Pb) had higher concentrations on MMPs than in sediments (Fig. 4.9). The mean concentration of Pb ranged from 19.843- 0.353 mgkg^{-1} for sediments and 123.06- 6.23 mgkg^{-1} for MMPs with Agbogbloshie (AG) recording the highest and Brekusu River (BR) the lowest. Brekusu Source (BS) had a relatively low amount of Pb but was slightly higher than Brekusu River (Br). Cu ranged from 62.01-0.28 mgkg^{-1} in sediments and 100.01-13.49 mgkg^{-1} in plastics. With Agbogbloshie recording the highest in Cu concentrations for sediments and plastics, Korle Beach (estuary) recording the least for plastics, and Brekusu Source (BS) for sediments.

Fe ranged from 13,362 mgkg^{-1} (Haatso, HF) to 556 mgkg^{-1} (Brekusu Source BS) in sediments and 9649 mgkg^{-1} (Haatso, HF) to 494 mgkg^{-1} (Brekusu River) in plastics. Zn in sediments ranges from 91.78-3.56 mgkg^{-1} and 180.67-20.01 mgkg^{-1} in plastics. Agbogbloshie and Korle Beach recorded the highest concentrations of Zn and Brekusu source and Brekusu River recorded the lowest concentrations for sediments and plastics respectively. A range of 45.31- 3.48 mgkg^{-1} was recorded for Cr in plastics, and 27.02-0.40 mgkg^{-1} was recorded for sediments. Haatso (HF) and Christian Village (CV) were the highest concentrations in sediments and plastics, respectively, whiles Korle Lagoon recorded the least for both sediments and plastics.

The results revealed a significant difference ($p<0.05$) for all heavy metals in both sediments and plastics except for iron in plastics which recorded a significant value of $p=0.104$.

The elements were evaluated by comparing the mean concentrations for the sample sites to the Canadian Council of Ministers of the Environment (CCME) guidelines for sediments (CCME, 2007) and the World Health Organisation and Food and Agriculture Organization (WHO/ FAO) guideline (WHO, 2001). The CCME guidelines for the heavy metals are 35 mg/kg, 35.7 mg/kg, 123 mg/kg, 37.5 mg/kg and 0.17 mg/kg for Pb, Cu, Zn, Cr and Hg, respectively. There are no guidelines for Fe in CCME. For WHO/ FAO guidelines for soil, the permissible concentrations for Pb, Cu, Zn, Cr and Hg are 50 mg/kg, 100mg/kg, 300mg/kg, 50mg/kg and 2.00mg/kg, respectively.

The mean concentrations of the elements Pb, Cu, Zn, Cr, Hg, and Fe in all sites along the Odaw River were below the WHO/FAO guideline; however, for CCME guidelines for sediments, Cu (62mg/kg) at Agbogbloshie (AG) was higher than the permissible limit. All other elements were below the permissible limits of CCME for sediments at all sites.

4.3.1 Heavy Metals Content in Sediments and Plastics (Meso/Microplastics)

Table 4. 6: Mean concentrations (mg/kg) of metals in plastics and surface sediments from Odaw River littoral zone.

	Pb		**Cu**		**Fe**		**Zn**		**Cr**		**Hg**	
Sites	Sediments	Plastics	Sediments	Plastics	Sediments	Plastics	Sediments	Plastics	Sediments	Plastics	Sediments	Plastics
KB	8.87	62.02	0.81	13.49	1595.58	6683.15	34.82	180.67	0.40	8.48	0.01	-
KL	16.42	99.99	26.82	10.25	13211.85	8264.71	84.73	86.82	17.71	3.48	0.04	-
AG	19.84	123.06	62.01	100.03	12859.97	6416.58	91.78	413.67	21.28	51.33	0.01	-
CV	7.10	26.18	0.24	21.13	3503.67	4363.36	19.26	14.04	16.48	45.31	-	-
HF	11.52	24.61	3.95	31.18	13362.58	9649.20	29.99	50.85	27.02	7.47	0.02	-
BR	0.35	6.23	0.48	24.86	853.60	494.43	5.32	20.01	5.24	23.41	-	-
BS	0.93	-	0.28	-	556.42	-	3.56	-	6.79	-	-	-

The unit of all concentrations was given in mg/kg (mg element per kg sample).

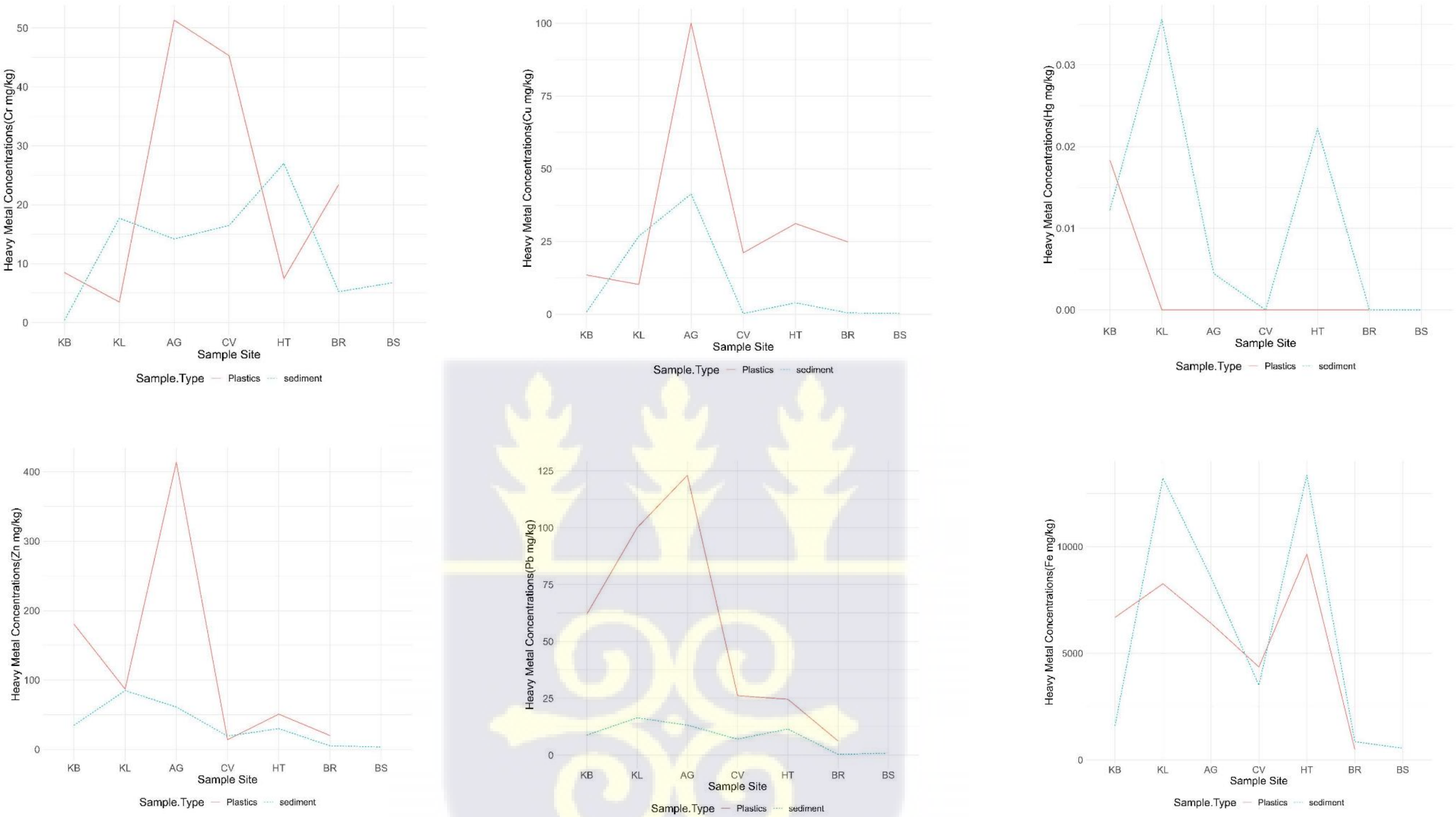


Fig. 4. 9: Heavy metal concentrations in MP particles and in soils (mg/kg) of each sampling site, blue and red lines indicate metal concentration extract from soil and MP particles

4.3.2 Correlation of Heavy Metals in Sediments and Meso/ Microplastics (MMPs)

The correlation between the concentrations of meso/microplastics (Table 4.8) and heavy metals in soils (Table 4.7) was assessed using Pearson's correlation coefficient. For correlation significance, the probability' criterion values ($p<0.05$) were applied. A substantial positive relationship between Pb/Zn ($r = 0.829^{**}$ /p=0.000), Cu/Zn ($r=0.640^{**}$/p=0.002), and Cu/Cr ($r = 0.712^{**}$/p=0.000) was found for the correlation of meso/microplastics samples with heavy metal concentrations, indicating that an increase in one metal concentration would likely result in an increase in the other as well. Furthermore, a high negative connection between Pb/Hg (r = -0.817/p=0.391) and Cu/Hg (r= -0.637/ p=0.560) implies that the concentration of one metal decreases with an increase in the other. Zn/Hg (r=0.575/ p=0.610) and Cr/Hg (r=0.504 /p=0.664) were shown to be moderately correlated (Table 4.7).

Pb/Fe ($r=0.741^{**}$/p=0.000), Pb/Cu (r=0.722**/ p=0.000), Pb/Zn (r=0.829**/p=0.000), Cu/Fe (r=0.647**/p=0.000)), Cu/Zn (r=0.817**/p=0.000), Fe/Zn (r=0.739**/p= 0.000), and Fe/Cr (r= 0.796**/p= 0.000) showed substantial positive correlations in sediment samples, indicating that a rise in one metal concentration would likely result in an increase in the other as well. Heavy metals in sediments showed no evidence of a negative association (Table 4.8).

Table 4. 7: Pearsons Correlation of Heavy Metals in Plastics

Elements	Pb	Cu	Fe	Zn	Cr	Hg
Pb	1	0.336 (0.136)	-0.100 (0.667)	.829** (0.000)	0.072(0.755)	-0.817(0.391)
Cu		1	0.173 (0.453)	.640**(0.002)	.712**(0.000)	-0.637 (0.560)
Fe			1	-0.103(0.657)	-0.197 (0.392)	-0.592 (0.597)
Zn				1	0.310 (0.171)	0.575 (0.610)
Cr					1	0.504 (0.664)
Hg						1

Table 4. 8: Pearsons Correlation of Heavy Metals in Sediments

Elements	Pb	Cu	Fe	Zn	Cr	Hg
Pb	1	.722**(0.000)	.741**(0.000)	.794**(0.000)	.488**(0.000)	0.219 (0.228)
Cu		1	.647**(0.000)	.817**(0.000)	.429**(0.001)	-0.171 (0.349)
Fe			1	.739**(0.000)	.796**(0.000)	0.233(0.199)
Zn				1	.383**(0.002)	0.233(0.200)
Cr					1	0.127(0.488)
Hg						1

**Correlation is significant at the 0.01 level (2-tailed).

4.3.3 Pollution and Ecological Risk Indicators of Heavy Metals in Sediments

4.3.3.1 Pollution Indices

Geoaccumulation index (Igeo)

Sediment quality was measured using the I_{geo} index of classification proposed by Muller (1981) (Table 4.9). The results of I_{geo} analysis indicated that all sites had low contamination levels of Pb Cu, Fe, Zn, Cr and Hg except Pb at Agbogbloshie (AG), which had a value of 0.082 which indicates that it is moderately contaminated as defined by the I_{geo} indicator, although its concentration exceeds the CCME guidelines. At the different locations, the remaining elements showed extremely low pollution.

Table 4. 9: Geoaccumulation Index Values

Sites	Pb	Cu	Fe	Zn	Cr	Hg
KB	-1.079	-6.672	-5.726	-1.592	-8.547	-3.404
KL	-0.191	-1.621	-2.676	-0.309	-3.082	-1.773
AG	0.082	-0.412	-2.715	-0.194	-2.817	-3.937
CV	-1.402	-8.405	-4.591	-2.447	-3.186	
HF	-0.702	-4.385	-2.660	-1.808	-2.473	-2.368
BR	-5.730	-7.425	-6.628	-4.302	-4.840	
BS	-4.337	-8.180	-7.246	-4.881	-4.465	

Contamination Factor (CF)and Pollution Load Index (PLI)

The CF values for Pb, Cu and Zn ($1 \leq CF \leq 3$) indicated moderate contamination at Korle Lagoon and Agbogbloshie. All other elements showed low contamination ($CF<1$) at all sites. The Pollution Load index was considerably low ($PLI<1$) for all sites indicating no to very low pollution in all sites for all elements.

Table 4. 10: Contamination Factor and Pollution Load Index of Heavy metals in soils at sampling sites

Sites	Pb	Cu	Fe	Zn	Cr	Hg	PLI
KB	0.710	0.015	0.028	0.497	0.004	0.142	**0.07**
KL	1.314	0.488	0.235	1.210	0.177	0.439	**0.49**
AG	1.587	1.127	0.228	1.311	0.213	0.098	**0.47**
CV	0.568	0.004	0.062	0.275	0.165	-	**0.09**
HF	0.922	0.072	0.237	0.428	0.270	0.291	**0.28**
BR	0.028	0.009	0.015	0.076	0.052	-	**0.03**
BS	0.074	0.005	0.010	0.051	0.068	-	**0.03**

4.3.3.2 Ecological Risk Indicators

Ecological Risk Factor (EF) and Ecological Risk Index (IR)

Both the Ecological Risk factor and Ecological Risk index for all the elements at all sites were lower than the baseline value; hence they were all under the low-risk category.

Table 4. 11: The Ecological Risk Factor and Risk Index of Heavy Metals at Sampling sites

Sites	**Pb**	**Cu**	**Zn**	**Cr**	**Hg**	**RI**
KB	6.568	2.438	1.210	0.354	17.556	**28.127**
KL	3.549	0.074	0.497	0.008	5.667	**9.795**
AG	7.937	5.637	1.311	0.426	3.917	**19.228**
CV	2.838	0.022	0.275	0.330	0.000	**3.465**
HF	4.609	0.359	0.428	0.540	11.625	**17.562**
BR	0.141	0.044	0.076	0.105	0.000	**0.366**
BS	0.371	0.026	0.051	0.136	0.000	**0.584**

Data Comparison with Previous Studies at the Agbogbloshie E-waste Site

The mean concentrations for samples collected from Agbogbloshie (sediments from Korle Lagoon) in this study were generally lower than the concentration for elements from previous studies for Agbogbloshie (Dismantling e-waste area) as illustrated in Table 4.12. Although data from earlier studies confirmed the presence of elevated levels of potentially toxic elements in soils at the Agbogbloshie e-waste burning and dismantling areas, this study states otherwise for sediments in the Korle Lagoon at Agbogbloshie.

Table 4. 12: Comparison of data on heavy metal concentration (mg/kg) in e-waste dumpsite at Agbogbloshie in Accra

Study	**Location**	**Pb**	**Cu**	**Fe**	**Zn**	**Cr**	**Hg**	**As**	**Cd**	**Sn**	**Ni**
Fosu-Mensah *et al*, 2017	Agbogbloshie	183.66	203.0	-	37.3	56	0.65	3.67	103.7	705.3	72.0
Vaccari *et al.*, 2019	Agbogbloshie	533	766	-	3205	3.1	-	43.8	2	-	-
Ackah, 2019	Agbogbloshie (Dismantling Area)	2380	11200	56800	1820	103	-	271	11	585	-
Cao *et al.*, 2020	Agbogbloshie	90	368	-	-	-	-	4.3	2.5	-	-
Dodd 2023	Agbogbloshie (Dismantling Area)	645	3257	-	1530	337	-	19	38	130	96
This Study	Agbogbloshie (sediments from Korle Lagoon))	19.8433	62.0067	12859.9667	91.7783	21.2833	0.0078	-	-	-	-
WHO		50	100	-	300	50	2	20	-	-	-
CCME (2007)		140	63	-	250	64	6.6	12	10	-	45
CCME (1999)		35	35.7	-	123	37	0.17	5.9	0.6	-	-

4.4 Social Interactions of Plastics Use

4.4.1 Demographics

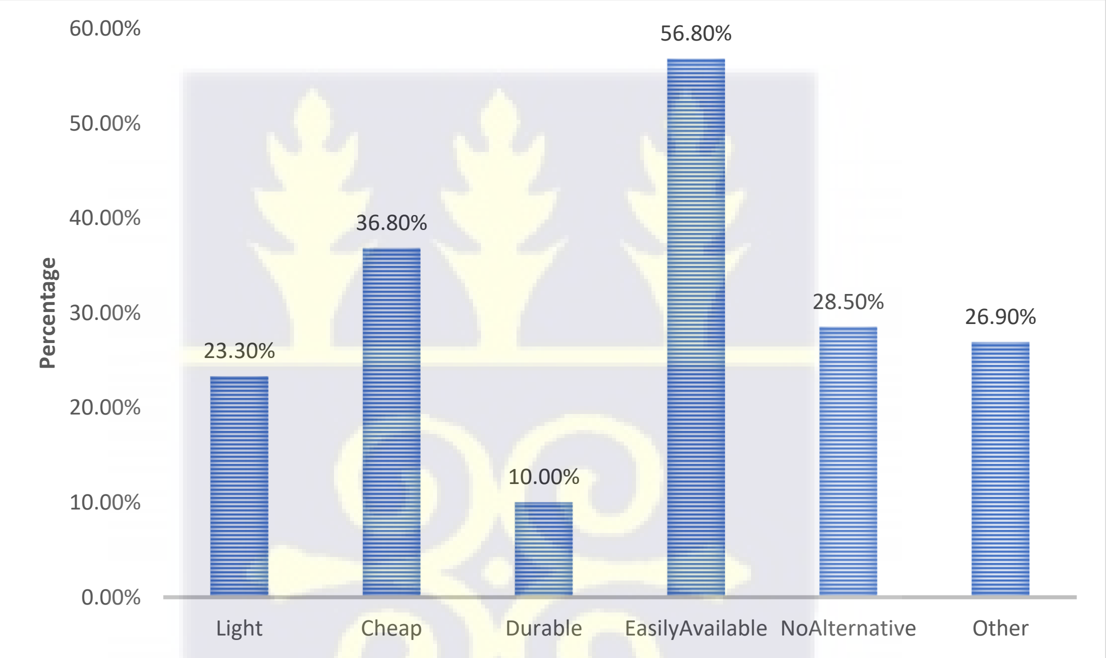
Table 4.13 provides an overview of the socio-demographic characteristics of respondents. It can be found that female respondents (52.14%) were more than male respondents (47.86%); however, the differences between male and female respondents were not significant. Two age ranges were the highest recorded, i.e., 18-24 years and 25-34 years. The educational level of most respondents was mainly secondary high school and tertiary, and the average highest monthly income of the respondents was around 200-500 GHC/month.

Table 4. 13: Socio-Demographic Characteristics of Respondents

Socio-Demographics		**Frequency**	**Proportions (%)**	**Sample Average**	
				Mean	**SD**
Gender	Male	279	47.86	0.49	0.49
	Female	304	52.14		
Age	12-17	84	14.41	2.75	1.16
	18-24	176	30.19		
	25-34	178	30.53		
	35-44	91	15.61		
	≥45	54	9.26		
Education	Primary	162	27.79	2.63	0.81
	Secondary	296	50.77		
	Tertiary	66	11.32		
	None	59	10.12		
Occupation	Formal	38	6.52	2.64	1.05
	Informal	72	12.35		
	Self employed	296	50.77		
	Unemployed	36	6.17		
	Student	141	24.19		
Income (GHC) per month	<200	149	25.56	2.25	0.99
	201-500	224	38.42		
	501-1000	130	22.30		
	1001-5000	78	13.38		
	>5000	2	0.34		
City	Old Fadama	157	26.93	2.07	0.85
	Christian Village/Haatso	198	33.96		
	Brekusu	228	39.79		
			47.86		

4.4.2 Consumption Behaviour

To assess the plastic consumption behaviour of respondents, multiple response questions were asked on why they preferred plastics and which types of plastics they use most often. Fig. 4.10 shows factors influencing plastic product use and preference over other products. From Fig.4.10, respondents report that they prefer plastics based on these three primary reasons in order of importance, easily available (56.8%), cheap (36.8%) and no alternative (28.5%). The lowest reason recorded was on the quality of the plastics produced, i.e., durability (10%).



*As a multiple response question, the total response will be greater than 100%
*Number of respondents=583

Fig. 4.10: Factors Influencing Plastic Consumption among Respondents

The descriptive analysis of preferred plastic products used often by respondents shows that plastic bags, which are single-use products, are the most used products (60%) followed by plastic buckets, plates, spoons, and storage containers, the second highest (28%). The lowest recorded products were disposable cups, straws and plates (Fig. 4.11).

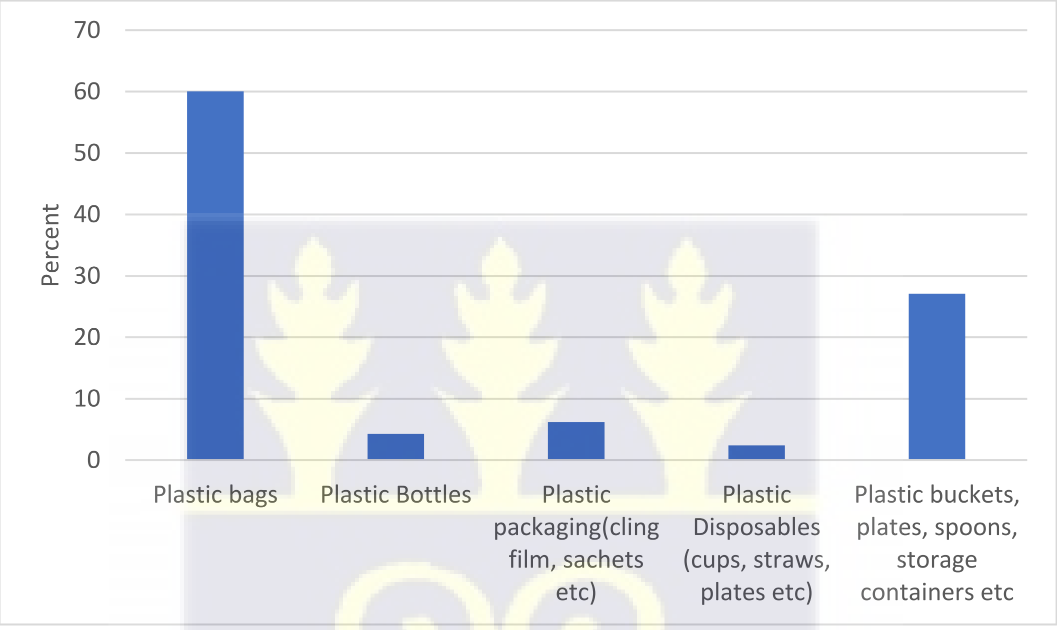


Fig. 4. 11: Plastic Product Preference of Respondents

Fig. 4.12 shows a cross-tabulation of occupation and preferred plastic usage. This indicates that the most used plastic products, Plastic bags and Plastic plates bowls, spoons, etc., were used most by self-employed people (N=180 for plastic bags and N= 79 for Plastic bowls, plates, spoons etc.). Students were the second highest (80 counts for plastic bags and 35 counts for plastic bowls, plates, spoons etc.). However, a Pearson's chi square test (χ^2= 19.240, df=16, ρ= 0.256) revealed no significant difference between the occupation groups.

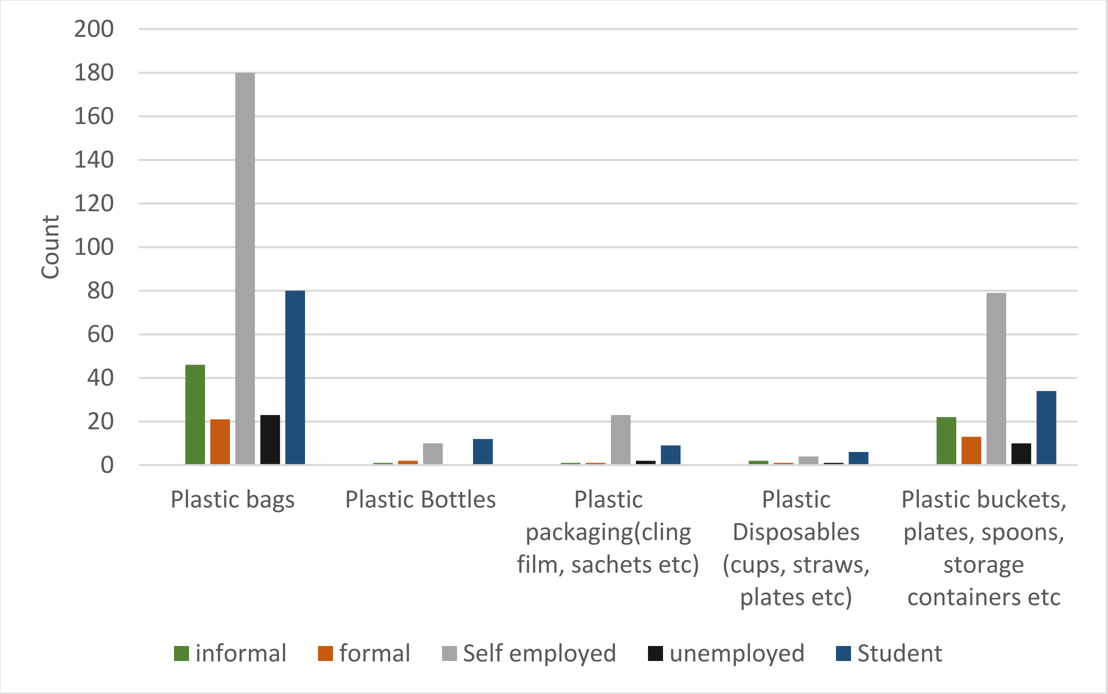


Fig. 4.12: Frequencies of Occupation types and Plastic product preferences.

Respondents were asked which bags they preferred to use when shopping, a cross-tabulation on age and preference of bags (Fig. 4.13) used when shopping showed plastic bags were used most for ages 25-34 years (count 140) followed by 18-24 years (count 135). The lowest age using plastic bags was >45 years (count 42). Cloth bags were the second most preferred bags, and with this, ages 18-24 years were the highest patrons of cloth bags, followed by 12-17 years (count 15). There was no significant difference within the ages and their preference of bags (χ^2= 12.547, df=12, ρ= 0.403)

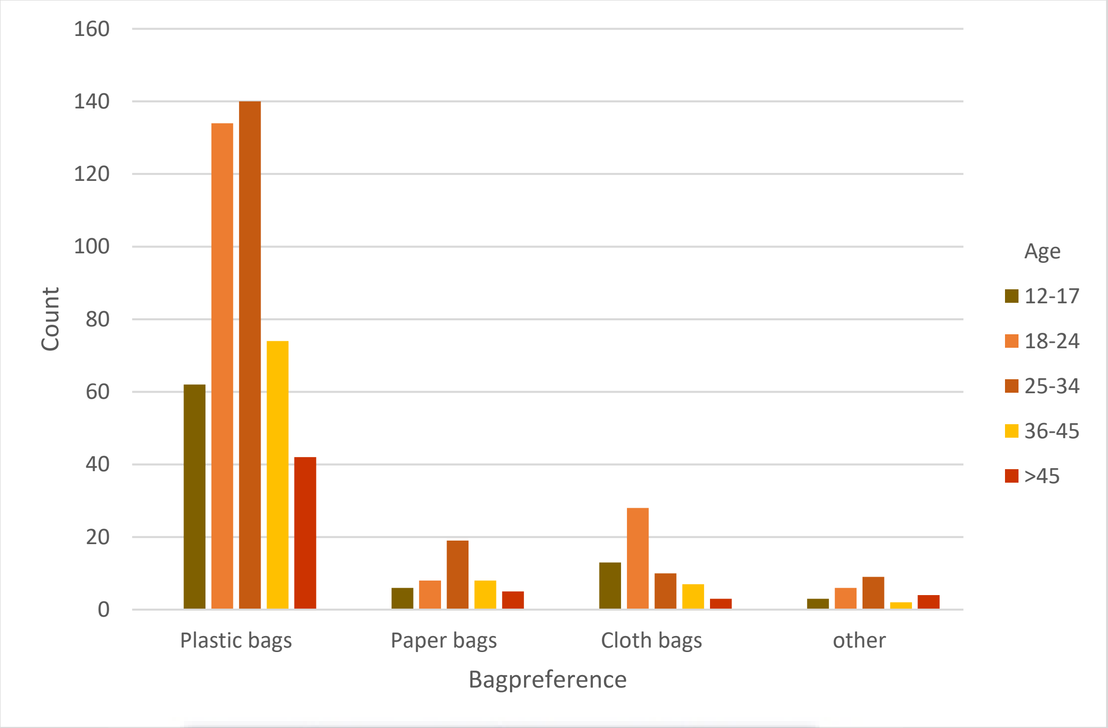


Fig. 4.13: Preference for types of Bags used for shopping by age

To assess the behaviour of respondents on plastic bag usage, three questions were asked to investigate why plastic bags were the most preferred. These questions included; do you carry your own bag for shopping? Which had a follow-up question of why they did not if they answered no. Additionally, they were asked how often they accepted plastic bags from shops. Table 4.14 shows the statistics for these questions. Most respondents do not carry their own bags for shopping (n=313). These were because most of them had plastic bags for free at the shops (mean=0.47). The mean for the question ‘do you accept plastic carry bags’ was 1.40, which show that most respondents do accept plastic bags.

Table 4.14: Statistics of Plastic Consumption Behaviour

Variables	Questions	Scale	N	Mean	SD
Behaviour	· Do you carry your own bag for shopping?	Yes = 1, Sometimes = 2, No = 3	583	2.27	2.20E-16
	· Why not?	I usually forget (Yes = 1, No = 0)	313	0.05	5.46E-45
		I get plastic bag for free (Yes = 1, No = 0)		0.48	5.56E-34
		I am not concerned with the type of bag I use for shopping (Yes = 1, No = 0)		0.08	5.56E-34
	· Do you accept plastic carry bags?	Accept it always = 1 Refuse it always and ask for paper/ cloth bags = 2 Refuse if having alternative carry bag =3		1.39	2.20E-16

4.4.2.1 Cluster Analysis for Plastic Use Behaviour

In the descriptive analysis, it was observed that the majority of respondents exhibited a strong inclination towards plastic usage, mainly single-use plastic carry bags. The cluster analysis conducted to assess attitudes towards plastic bags identified two distinct clusters based on the collected data. Cluster 2 (n=219) represented the minority and preferred to carry their own bags, refuse plastic carry bags, practice waste separation, and recycle plastic waste. In contrast, Cluster 1 (n=364) comprised respondents who preferred using plastic carry bags and did not practice plastic separation or recycling. A detailed overview of the clusters and their corresponding variables can be found in Table 4.15.

Table 4.15: Plastic use behaviour-based Clusters

Cluster variable	**Sample (n=583) mean scores**	**Cluster 2 (37.6%, n=219)**	**Cluster 1 (62.4%, n=364)**
Do you carry your own bag for shopping?	1.93	2.34	1.69
Do you accept plastic carry bags?	1.27	1.73	1.00
Do you separate plastic waste	1.75	1.95	1.61
Do you recycle plastic bags	1.91	2.20	1.73

In line with their aversion towards single-use plastic bags, individuals belonging to Cluster 2 demonstrate positive behaviour across all assessed variables. The behavioural indicators suggest that these individuals are strongly inclined to reduce their consumption of single-use plastic bags by actively avoiding them when alternatives are available, declining their usage even when offered for free, and demonstrating a willingness to sustainably manage their plastic waste through recycling. Therefore, this cluster is appropriately labelled as "*Abstainers*" reflecting their anti-single-use plastic bag behaviour, avoidance of such bags, and commitment to recycling.

Conversely, members of Cluster 1 exhibit behaviour that favours the consumption of plastic bags and display poor management of their plastic waste. As indicated in Table 4.15, Cluster 1 has the lowest behavioural scores across all aspects related to single-use bags. These individuals can be considered avid consumers of single-use plastic bags, thus earning the label "*Advocates*."

To examine the identity profiles of the clusters further, a chi-square test of independence was conducted to analyse the association between socio-demographic characteristics of the respondents and the clusters (Table 4.16). The results indicated that the variables assessed displayed statistically significant differences across six socio-demographic characteristics of the respondents (Table 4.16).

A higher proportion of males (n=186), respondents aged between 18-24 years (n=118), individuals educated to the secondary level (n=179), those who were self-employed (n=187), individuals with an income between GHC 201-500 (n=144), and respondents from Brekusu (n=142) were found to have the highest representation in the "*Advocates*" cluster. Generally, a higher proportion of all assessed variables fell under the "*Advocates*" category. On the other hand, a higher proportion of respondents with higher levels of educational attainment were categorised as "*Abstainers*" with those having tertiary education showing the highest numbers (n=42). Education ($\chi2=31.428$, $\rho=6.9E-7$) and occupation ($\chi2=13.514$, $\rho=0.009$) were identified as the two significant factors in determining the clusters.

Table 4.16: Cluster Profiles by Socio-demographic characteristics

Socio-Demographics		**Abstainers (Cluster 1)**	**Advocates (Cluster 2)**	χ^2 ***(ρ-value)***
Gender				0.019(0.890)
	Male	115	189	
	Female	104	175	
Age				4.833(0.305)
	12-17	31	53	
	18-24	58	118	
	25-34	76	102	
	35-44	37	54	
	≥45	17	37	
Education				31.428 (6.9E-7)
	Primary	48	114	
	Secondary	117	179	
	Tertiary	42	24	
	None	12	47	
Occupation				13.514 (0.009)
	Formal	23	15	
	Informal	20	52	
	Self employed	109	187	
	Unemployed	10	26	
	Student	57	84	
Income GHC				5.156 (0.272)
	<200	53	96	
	201-500	80	144	
	501-1000	50	80	
	1001-5000	34	44	
	>5000	2	0	
City				3.968(1.38)
	Old Fadama	49	108	
	CHR/HAA	80	114	
	Brekusu	90	142	

4.4.3 Waste Management

One of the categories measured for respondents' activities was waste management, specifically how they dispose of plastic waste. Respondents were asked several questions, including whether they separate plastic waste from other household waste products. The results showed (Fig 4.14) that 55.9% of respondents do not separate their plastic waste, while 35.5% engage in waste separation. However, a small percentage of respondents (1.02%) reported being unaware of waste separation.

According to the respondents, the main reason for separating plastic waste was the ability to sell water sachet bags to collectors who recycle them. Others mentioned recycling single-use plastic bags by using them as fuel for burning.

A cross-tabulation analysis (Fig 4.15) was conducted to examine the relationship between waste disposal forms and the four communities surveyed (Old Fadama, Christian Village/Haatso (CHR/HAA), and Brekusu). In Old Fadama, the majority of people (70%) hand over their waste to waste collectors or use the municipal corporation collection bins. Open dumping (4.45%) and burning (7.00%) were this community's least common forms of waste disposal. In contrast, in Brekusu, burning was the most prevalent form of waste disposal (62.93%), while using municipal corporation collection bins was the least common (7.32%).

Fig. 4.14: Frequency of waste separation done by respondents

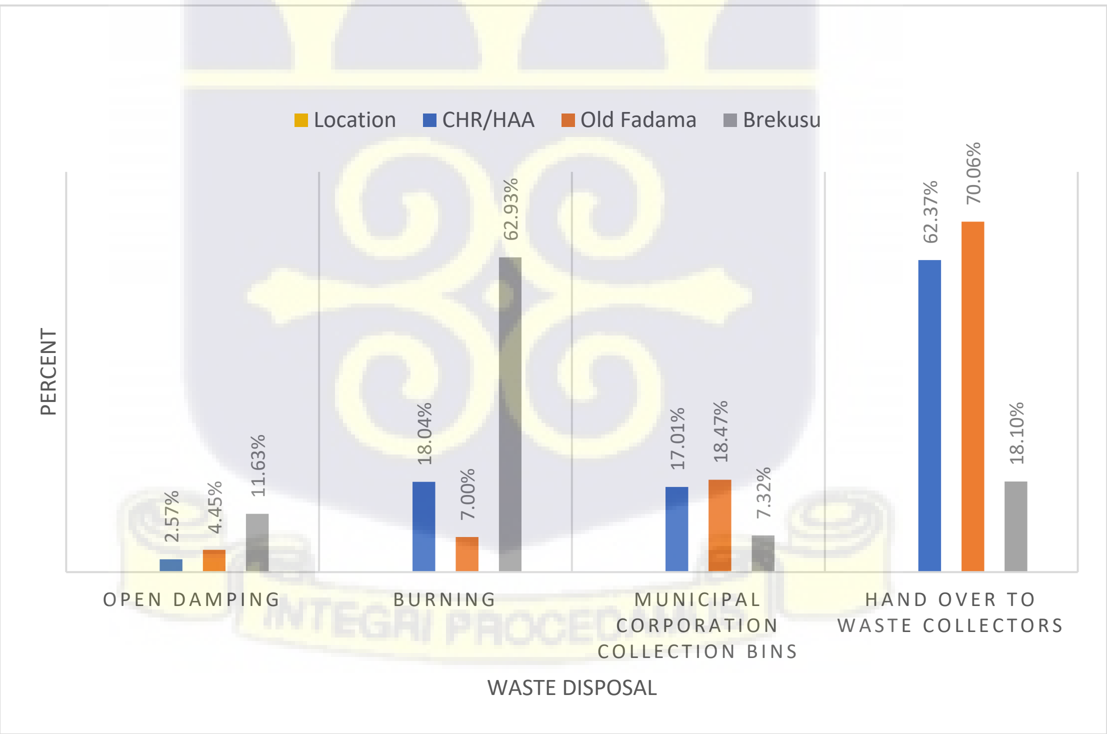


Fig. 4.15: Forms of Waste Disposal in the Various Communities Surveyed

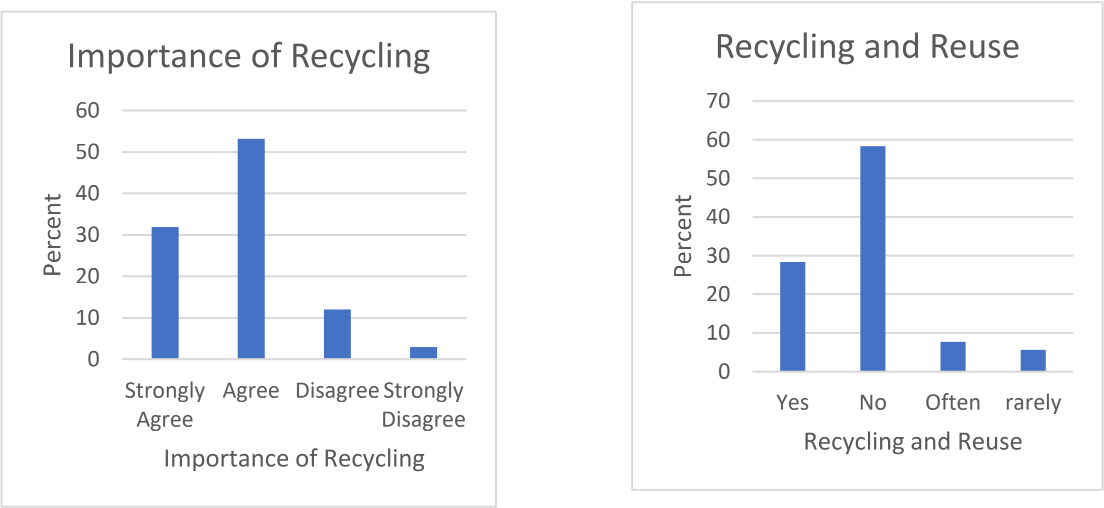


Fig. 4.16: Recycling and Reuse of Plastic Products among Respondents

To delve deeper into the behaviour of respondents regarding waste management, they were asked about the importance of recycling and whether they reuse or recycle single-use plastic carry bags (Fig 4.16). The results revealed that 53% of respondents agreed on the importance of recycling. However, a significant number of respondents (58.31%) admitted not recycling their plastic waste.

The reasons varied for respondents who indicated that they do not recycle. The majority (63.40%) stated that disposing of their plastic waste without recycling was easy. Some respondents also expressed a lack of concern or motivation to recycle (22.20%). In comparison, a small percentage (8%) mentioned being unaware of recycling as a reason for not engaging in the practice (Table. 4.17).

Table 4.17: Reasons for Not Recycling Waste Plastic Products

		Responses		Percent of Cases
		N	Percent	
Recycle	Not Aware	31	8.10%	9.20%
	Not Bothered	85	22.20%	25.20%
	Easy Disposing	243	63.40%	72.10%
	Other Reason	24	6.30%	7.10%
Total		383	100.00%	113.60%

4.4.3.1 Waste Separation and Demographics

A binary logistic regression analysis was conducted to investigate the association between socio-demographic factors and the likelihood of waste separation. A preliminary analysis was performed to assess the assumption of multi-collinearity, which indicated that the tolerance values ranged from 0.658 to 0.963, suggesting no significant issue with multicollinearity. Furthermore, no outliers were identified based on the standardised residual values.

The logistic regression model did not yield a statistically significant result, as indicated by the chi-square test ($\chi 2$) = 8.364, p=0.213 (df=6, N=583). The model's overall predictive power, measured by the percentage of cases correctly classified, was 57.6%. Examining the contribution of individual predictors to the model (Table 4.18), it was found that location emerged as a significant factor. The odds ratio for location was 0.207, indicating that participants from specific locations were 0.207 times less likely to engage in waste separation than other participants.

These findings suggest that the socio-demographic factors examined in this study did not demonstrate a significant association with the likelihood of waste separation. However, location appeared to play a notable role, with participants from specific locations being less inclined to separate their waste.

Table 4.18: Logistic Regression model predicting the likelihood of Waste Separation by Demographics

	B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for EXP(B)	
							Lower	Upper
Sex	0.04	0.174	0.053	1	0.818	1.041	0.739	1.465
Age	-0.093	0.091	1.056	1	0.304	0.911	0.763	1.088
Education	-0.074	0.1	0.554	1	0.457	0.928	0.763	1.129
Occupation	-0.023	0.082	0.082	1	0.775	0.977	0.832	1.147
Income	-0.076	0.106	0.512	1	0.474	0.927	0.752	1.142
Location	0.207	0.102	4.076	1	0.043	1.23	1.006	1.503
Constant	0.07	0.491	0.021	1	0.886	1.073		

a Variable(s) entered on step 1: Sex, Age, Education, Occupation, Income, Location.

4.4.3.1 Plastics Management

Respondents were presented with two options to consider for managing plastics by the government: (i) implementing a ban on plastics and (ii) whether they would be willing to pay an extra amount for reusable alternatives. The findings, as shown in Fig. 4.17, indicate that 36.71% of respondents agreed, and 26.24% strongly agreed with the ban on plastics. On the other hand, 42.88% disagreed, and 16.98% strongly disagreed with the notion of paying extra for reusable alternatives.

Statistical analysis using the t-test revealed that both questions yielded significant results (p=0.000) (Table 4.19), indicating a substantial difference in the responses between the groups. These findings suggest that many respondents supported a ban on plastics, while a majority expressed reluctance or opposition towards paying extra for reusable alternatives. These results indicate the need for further examination and consideration of the feasibility and acceptability of implementing such measures in managing plastics.

Table 4. 19: One-Sample Test for plastic management options assessed

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Ban on plastics	55.939	582	.000	2.616	2.52	2.71
will you pay for reusable alternative	55.305	582	.000	2.479	2.39	2.57

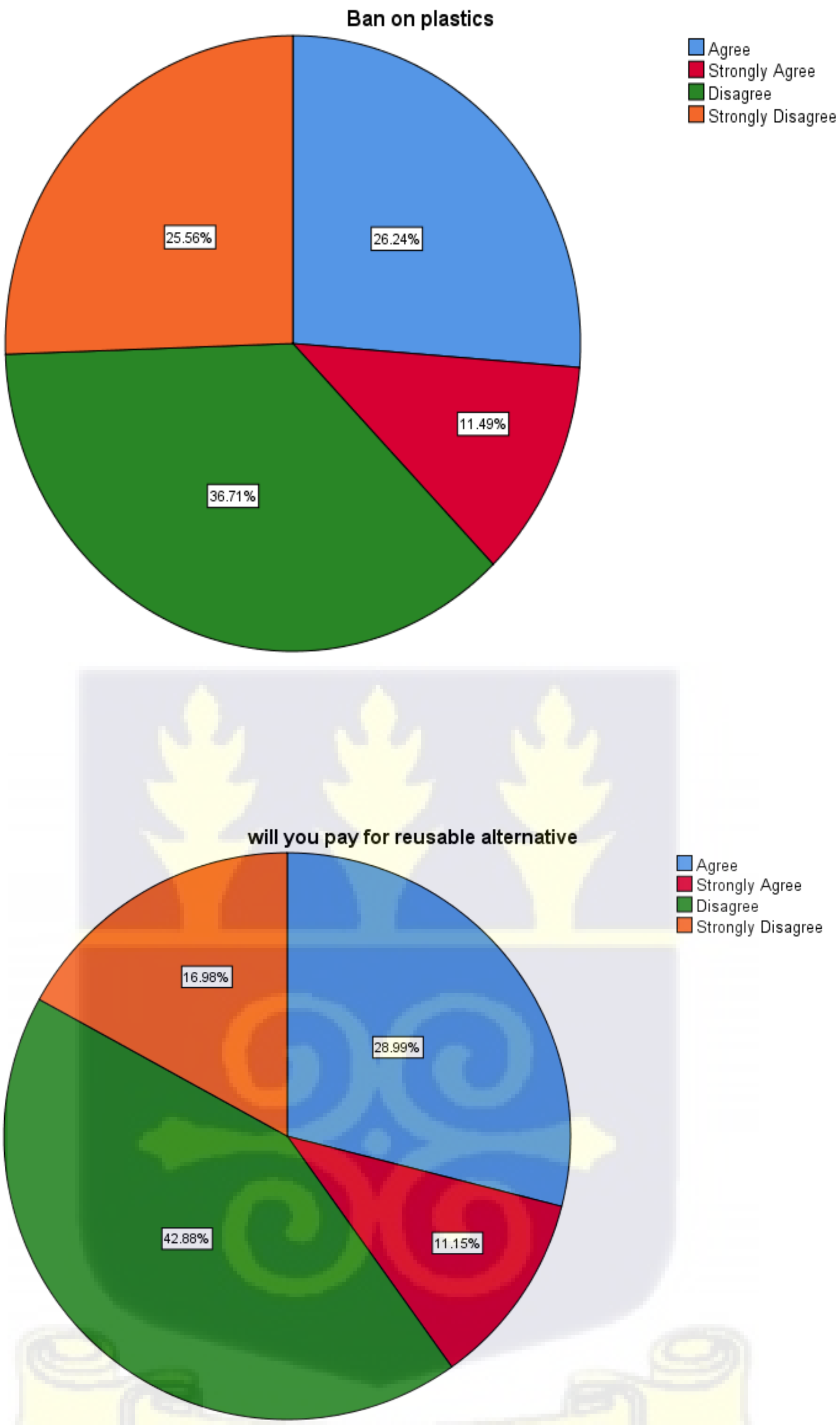


Fig. 4.17: Frequency of Plastic Manage Options (Ban/ Pay extra for reusable alternatives) by Respondents

4.4.4 Risk Perception

To examine the risk perception of the respondents, a series of questions were administered to assess their awareness of the threats posed by plastics to humans and the environment, as well as the potential risks associated with the chemical contents of plastics. A cross-tabulation analysis was performed to explore the relationship between the respondents' education level and their perception of the threat of plastics (Fig. 4.18). The findings indicated that the respondents showed a considerable understanding of the risks associated with plastics, recognizing them as a threat to human health and the environment.

Fig. 4.18 illustrates the distribution of responses to the question, "Do you think plastic waste is a problem to human health and the environment?" Among the respondents, a majority provided an affirmative answer (Yes, 80%), indicating their recognition of the detrimental impact of plastic waste; 13% of respondents indicated that plastics were not harmful to human health or the environment and 7% were not sure if plastics had any impacts. Furthermore, the analysis of the cross-tabulation highlighted that the perception of plastic waste as a threat was consistent across different educational backgrounds. The highest proportion of respondents who acknowledged the threat of plastics were those with secondary education (42%), followed by respondents with primary education (21%), tertiary education (n=10%), and no formal education (6%). It is worth noting that the number of respondents who answered "no" or expressed uncertainty was minimal compared to those who responded positively. These results suggest that most respondents clearly understood the risks associated with plastic waste, irrespective of their educational attainment.

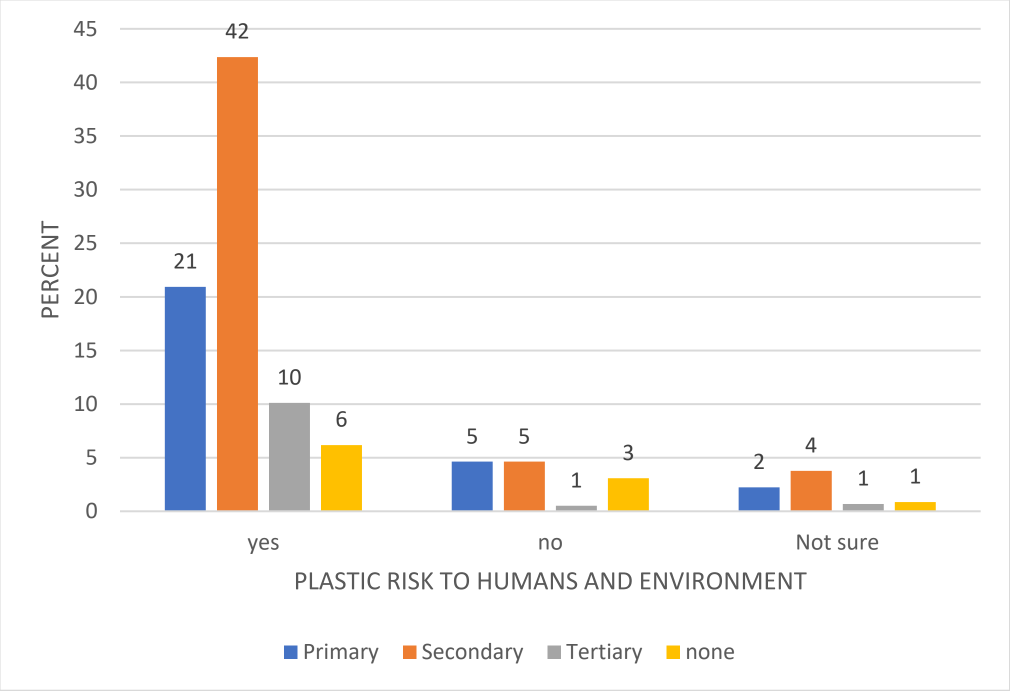


Fig. 4.18: Threat of Plastics to Human Health and the Environment.

When the respondents were asked about the impacts of plastics on the environment, the highest score was recorded for clogging drains (n=208), followed by making the city dirty (n=207). Conversely, the least recorded impact was severely impacting animals and birds (n=87). This is shown in Table 4.20.

To further assess the perceived severity of the threats posed by plastics to various environments, the respondents were asked to rate the responses on a scale of 1 to 4, with 1 indicating very serious threat and 4 indicating not serious threat. The results show that the respondents generally agreed that plastics significantly threatened freshwater, marine ecosystems, wildlife environments, and human health. The mean ratings for these categories ranged between 1.79 and 2.39, suggesting that the respondents considered these threats to be serious (Table 4.21).

These findings highlight the recognition among the respondents of the negative impacts of plastics on the environment, particularly in terms of clogging drains and making cities dirty. Furthermore, the respondents perceived plastics as posing significant threats to freshwater and marine ecosystems, wildlife environments, and human health, emphasizing the need to address these concerns and promote sustainable practices to mitigate the harmful effects of plastics.

Table 4.20: Frequencies of Impacts of Plastics on the Environment

		Responses		Percent of Cases
		N	Percent	
Plastics Impact	Makes City Dirty	207	17.10	44.70
	Pollutes Water bodies	187	15.50	40.40
	Introduces Chemicals to the Environment	172	14.20	37.10
	Severely Impacts Animals and Birds	82	6.80	17.70
	Causes Diseases in Humans	202	16.70	43.60
	Clogs Drains	208	17.20	44.90
	All of the Above	152	12.60	32.80
Total		1210	100.00	261.30

Table 4.21:Frequency Table for Threats of Plastics to the Environment and Human Health

	N	**Mean**	**Std. Deviation**	**Minimum**	**Maximum**
Freshwater	583	2.31	1.009	1	4
Marine	583	2.33	0.959	1	4
Wildlife	583	2.39	1.041	1	4
Human Health	583	1.78	0.902	1	4

A Chi-square test was conducted to examine the relationship between the perceived threats of plastic and two demographic variables; age and education. The results revealed a significant relationship between age and the perception of plastic as a threat ($\chi2=9.648$, df=4, $\rho=0.047$). This indicates that age had an impact on the respondents' responses regarding whether they perceived plastics as a threat or not.

Similarly, the Chi-square test showed a significant relationship between education and the perception of plastic as a threat ($\chi2=13.223$, df=3, $\rho=0.004$).

4.4.5 Knowledge of MPs

Generally, a significant number of respondents had limited knowledge about microplastics, regardless of their educational level. Figure 4.19 illustrates the respondents' understanding of microplastics and the associated risks. More precisely, individuals with secondary level education (n=254), primary education (n=154), tertiary education (n=51), and no formal education (n=55) specifically expressed a lack of knowledge regarding what microplastics are. Additionally, 90% of these respondents were unaware of the risks that microplastics pose to human health.

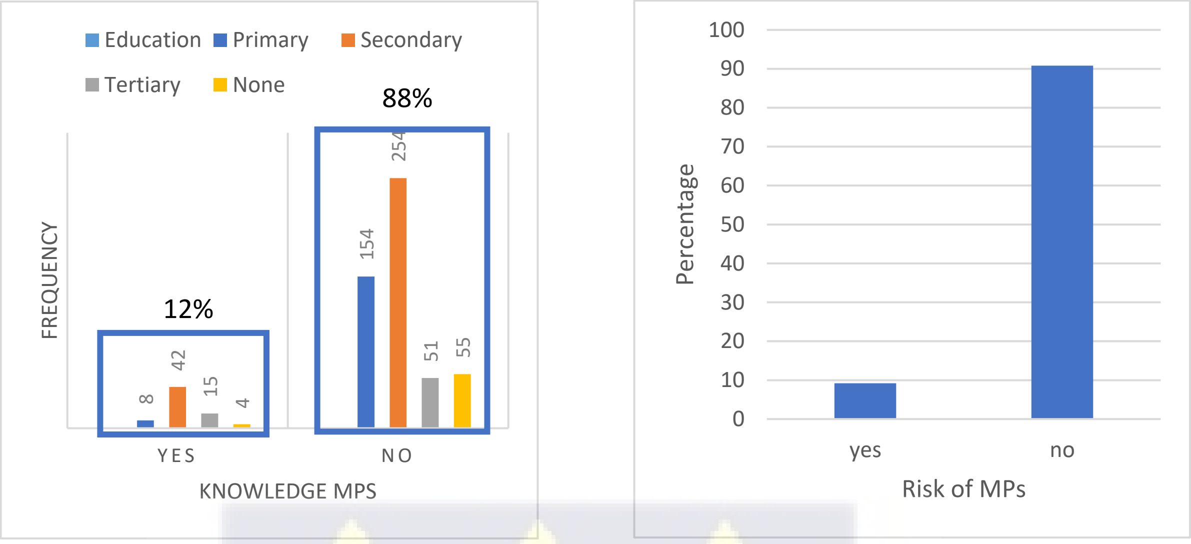


Fig. 4.19: Knowledge and Risk Perception of Respondents on Microplastics

4.4.6 Structural Equation Modelling

Table 4.22: Model Latent Factor with corresponding Observed indicators and descriptions.

Latent Variable	Observed Variable	Questions
Plastic Use behaviour (PUB)	PUB1	Which type of bags do you prefer to use?
	PUB2	Do you carry your own bag for shopping?
	PUB3	If a shop keeper gives you plastic carry bag, what is your reaction?
Plastic Waste Management (PWM)	PWM1	Do you reuse/ recycle single use plastic carry bags?
	PWM2	Do you separate plastic waste from other waste products in your house?
	PWM3	How do you dispose of plastic waste?
Risk Perception (RIP)	RIP1	Do you think plastic waste is a problem for human health and the environment?
	RIP2	Are you aware chemicals from plastic compounds used in plastic products leaks from the plastic and have harmful impacts?
	RIP3	How serious a threat do you think plastic cause Freshwater Environments?
Knowledge of MPs (KMP)	KMP1	Have you heard of microplastics?
	KMP2	Do you know that microplastics serve as surfaces for other pollutants and microorganisms?
	KMP3	Do you know that microplastics have been found in human bodies?

4.4.6.1 Measurement Model Fit Assessment

The measurement model fit was assessed using SEM and confirmatory factor analysis (CFA) in AMOS version 26. The latent variables of Plastic Use Behavior, Plastic Waste Management, Risk Perception, and Knowledge of MPs were utilised in the analysis, as presented in Table 4.22. The unconstrained model fit measures were evaluated, and the chi-square goodness-of-fit test yielded a significant result (p-value >0.001). The $\chi 2$/df ratio was 1.723, indicating a good fit to the data. The RMSEA (Root Mean Square Error of Approximation) value was excellent at 0.035, and the pClose test resulted in a non-significant p-value of 1.000, suggesting a good fit as well.

The other fit indices, such as the Comparative Fit Index (CFI) with a value of 0.977, the Tucker-Lewis Index (TLI) with a value of 0.907, and the Incremental Fit Index (IFI) with a value of 0.934, were all greater than the recommended threshold of 0.90. Although the TLI value (0.884) fell slightly below the threshold, it still remained in an acceptable range.

All the fit indices for the measurement model of the latent factors exceeded the recommended threshold values, as presented in Table 4.23. Consequently, the measurement model fit of the four latent factors and observed variables was deemed satisfactory.

Large sample size and the complexity of the measurement model may account for the significant values obtained ($p < 0.05$). The significance does not indicate a poor fit, as the model is sensitive to both a complex structure and a large sample size. The current measurement model does not impose any artificial limitations on the measurements. In general, the fit indices of the model indicate that it is well-suited for representing the measurements.

Table 4.23: Model Fit Measurements for Structural Equation Model.

Criterion of Model fit	**Absolute Fit Acceptance**	**Sources**	**Values of Model fit**	**Test Result**
RMSEA	≤ 0.08	*Hu and Bentler (1998)*	0.035	Confirmed
SRMR	≤ 0.08		0.036	Confirmed
pClose	>0.05		0.974	Confirmed
GFI	GFI ≥ 0.90	*Hair* et al *(2010)*	0.977	Confirmed
AGFI	AGFI ≥ 0.90		0.963	Confirmed
CFI	CFI ≥ 0.90	*Bentler (1990)*	0.932	Confirmed
IFI	IFI ≥ 0.90		0.934	Confirmed
TLI	TFI ≥ 0.90		0.907	Confirmed
χ^2 /df	3-5	*Schumacker and Lomax (2004)*	1.723	Confirmed

Table 4.24: Hypothesis Analytics

Hypothesis Path relationship			**Estimate**	**S.E.**	**C.R.**	**P-value**
PWM	<-->	RIP	0.03	0.01	2.868	0.004
PUB	<-->	PWM	0.028	0.014	1.993	0.046
PUB	<-->	RIP	0.004	0.002	1.631	0.103
RIP	<-->	KMP	-0.001	0.001	-1.109	0.267
PWM	<-->	KMP	0.003	0.005	0.547	0.584
PUB	<-->	KMP	0.001	0.001	1.085	0.278

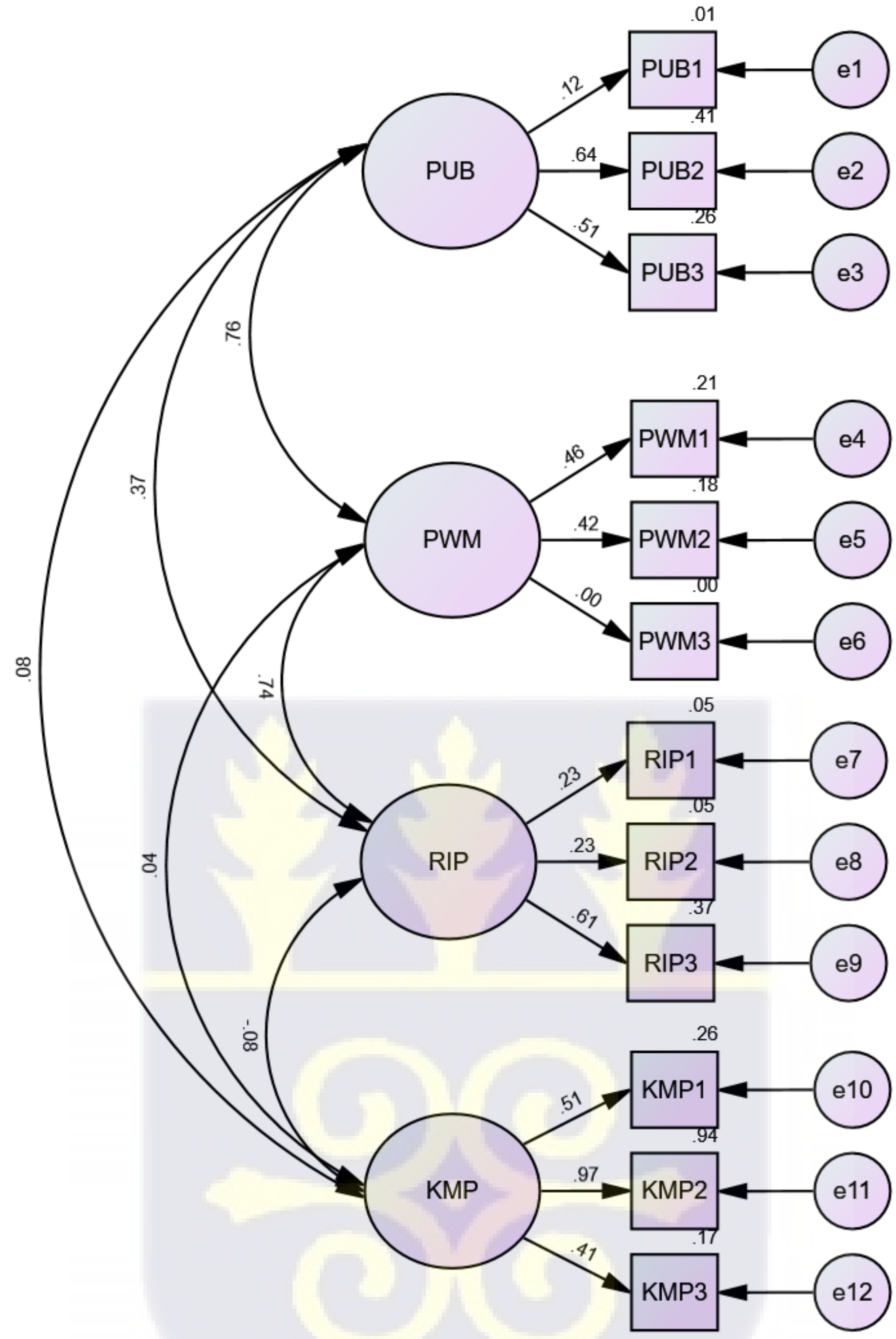


Fig. 4.20: Path Coefficient between Three Latent Variables on Current Design.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

Congruent with the preceding chapters, this chapter is structured around three primary categories: Occurrence, Interaction with Heavy Metals, and Social Interactions. This chapter expounds upon the findings derived from the study. It commences by delving into the abundance spatial and temporal distribution of microplastics within the Odaw River, presenting an in-depth analysis of the types, forms, and ecological risk associated with MPs present in the river. Subsequently, this chapter explores the outcomes of the interactions between heavy metals within the river ecosystem, MPs, and sediments, shedding light on the intricate dynamics at play in this complex environment. Finally, the chapter concludes by elucidating the results pertaining to the social interactions and ramifications of plastic usage among the communities situated within the Odaw River Catchment. Through a comprehensive examination of these facets, this chapter contributes valuable insights to the broader discourse on microplastics and their multifaceted impacts within the Odaw River ecosystem.

5.2 Microplastics Occurrence in the Odaw River

5.2.1 Abundance, Spatial and Temporal Distribution of Microplastic

The analysis of water and sediment samples taken from the Odaw River indicates that the river is contaminated by MPs (Fig 5.2). As observed in numerous studies (Ryan, 2015; Ballent *et al*., 2016; Klein *et al*., 2015; Mani *et al*., 2015), a significant proportion of MPs in the environment consists of secondary microplastics. This study suggests that microplastics originate mostly from terrestrial sources. Due to the durability and elasticity of plastics, the breakdown of microplastics in water takes decades (Weinstein *et al*., 2016). Plastic waste introduced into rivers might not have sufficient time to undergo significant fragmentation. Consequently, the notable prevalence of larger plastic debris at specific sites suggests that MPs in these locations could have undergone fragmentation on land (Mani *et al*., 2015) prior to entering the river or might have experienced initial degradation within the river itself. Earlier research (Ballent *et al*., 2016; Klein *et al*., 2015) focusing on inland water bodies has demonstrated that urban and developed regions can serve as potential sources of microplastics.

Generally, water and sediment samples across all 16 sampling sites were significant ($p<0.05$). The spatial distribution of MPs along the Odaw River exhibits increasing MPs contamination from upstream to downstream, as observed in water and sediment (Table 5.3 and Figure 5.2). This difference in MPs abundance could be attributed to the closeness of all sampling sites to sources of microplastics, including industrial activities, urbanisation, and wastewater discharge into the river. Such proximity increases the likelihood of microplastics being present across all sites. Additionally, factors such as flow velocity, unique plastic characteristics, biofouling, and adsorption to other substances are likely to influence the spatial distribution (within the water column or sediment) as well as the temporal detection of MPs (Andrady, 2011; Cole *et al*., 2013; Zalasiewicz *et al*., 2016)

The sampling sites chosen for this study were grouped into four zones characterised by their land use and land cover purposes. Some sites had high levels of industrialisation and urbanisation, i.e. (Commercial/ industrial zone, e.g., Alajo and Agbogbloshie and Urban residential/ Agricultural zones, e.g., Christian Village and Agbogba). Other areas, like the periurban and rural zones (e.g., Kuotam and Brekusu), had small populations compared to the others. These zones were strategically selected to explore the impact of some human activities on MPs contamination. Higher levels of microplastics were recorded in the urban residential/agriculture and commercial/industrial zones of the Odaw River, aligning with other studies by Nel *et al*., 2017; and Lambert and Wagner 2018 that link elevated contamination levels to densely populated urban regions. Kataoka *et al*. (2019) noted that increased microplastic contamination in river ecosystems is most pronounced in rivers characterised by poor water quality, primarily attributed to high population density and urbanisation. Consequently, high levels of MPs were recorded at sites (Agbogbloshie and Alajo) with relatively poor water quality compared to other sites. Thus, a positive correlation exists between decreasing water quality and the substantial rise in microplastic concentrations.

Based on the findings, the natural inquiry arises as to why microplastic concentrations exhibit notable elevation in polluted areas. Kataoka *et al*., 2019 posit that an explanation for this phenomenon resides in the shared characteristics of the source and flow processes between microplastics and pollutants. Generally, pollutants are categorised into point or non-point sources. These point sources encompass household discharges, livestock and agricultural waste, industrial and commercial activities, and wastewater treatment plants (WWTPs), while non-point sources encompass forested, urban, and agricultural landscapes (Turan *et al*., 2021). Consequently, the increase in loads of pollutant from both point and non-point sources aligns with population growth and urban development. This correspondence provides a potential rationale for the observed heightened microplastic concentrations within polluted river basins.

Additionally, Li *et al.*, (2021) posited that coastal urban areas exhibit heightened concentrations of microplastics due to increased population density. The current study concurs with this notion, as regions with high anthropogenic activities and population density within the Odaw River catchment area displayed relatively elevated levels of microplastic contamination (Table 5.3) compared to areas with relatively less human activity and population. This correlation emphasises the role of anthropogenic activities and urbanisation in exacerbating MPs pollution within riverine ecosystems.

Rivers serve as sinks and conduits for the transportation of microplastics from inland sources to coastal regions (Haberstroh *et al.*, 2021). There was a progressive increase in the concentrations of MPs in sediment from upstream of the Odaw river to downstream at the estuary, indicating the tendency of MPs to settle into sediment downstream. Upstream and midstream portions of the river serve as temporary sinks for MPs, where they are later transported downstream and accumulate for a more extended period. In contrast, the estuary area displayed low MPs concentrations in sediment, averaging as compared to higher concentrations at Agbogbloshie. Various factors, including geographical features, tidal currents, (Xu *et al*., 2020), flow velocity, and MPs characteristics, can influence MPs abundance (Liu *et al*., 2020). This observation aligns with other findings that sediment is a prominent repository for MPs in river systems. Water samples, however, had high concentrations of microplastics observed at the estuary (Korle Gonno) downstream of the Odaw River. This may be attributed to the accumulation of these particles due to water flow dynamics. The estuarine zone serves as a natural trap for microplastics, accentuating the need for comprehensive strategies to mitigate their entry into marine ecosystems (Laursen *et al.*, 2023).

The intensity and amount of rainfall significantly determine the magnitude of runoff and water quality discharged into a watershed. Thus, rainfall and flow indicators carry essential information regarding plastic transport dynamics (Haberstroh *et al*., 2021). Given this, the seasonal variations in the load of MPs within the Odaw River were assessed. The investigation identified seasonal fluctuations in microplastic concentrations, evident in both sediment and water samples, as depicted in Figure 5.3 and Table 5.4. As expected, seasonal patterns indicated a higher abundance of microplastics in water samples during the wet season and a lower concentration in sediment. This correlation arises from the intensified rainfall in the wet season compared to decreased or no rain experienced in the dry season. Generally, microplastic abundance was more significant in the wet season than in the dry season. Despite this trend, no statistically significant disparities in microplastic concentrations were observed between water and sediment samples ($p<0.05$) (Table 5.4). These outcomes deviated from the initial assumption.

During the rainy season, specific sites exhibited escalated concentrations of suspended microplastics. This escalation could be attributed to the in-flow of MPs through surface runoff (Wagner *et al*., 2014) and the resuspension of microplastic-laden sediment stemming (Li *et al*., 2018) from the increase in suspended solid loads of the river during events such as rainstorms (Hurley & Nizzetto, 2018). Additionally, it is pertinent to consider whether the accumulation of microplastics in sediment is continuous or transient over short periods. This information is essential for developing effective mitigation and remediation strategies to safeguard the environment and its inhabitants.

The findings of this study emphasises the influence of seasonal conditions on particle deposition and retention mechanisms, with parameters like flow velocity coming into play. Importantly, this study's results indicate that microplastic pollution varies during seasons of the year(s), suggesting that although the impact of MPs is continuous, impacts are escalated in the wet seasons.

When compared to similar investigations in other aquatic systems within Ghana, the presence of microplastics (MPs) in the Odaw River water exceeds the levels reported in rivers (Blankson *et al*., 2022) and coastal mangrove ecosystems (Chico-Ortiz *et al*., 2020). This difference may stem from variations in the sampling techniques employed in each study. Notably, the absence of a universally standardised method for microplastic sampling contributes to the challenge of comparing findings across different studies. Consequently, the differences in the particle counts in water may be as a result of differences in methodological approaches, such as the lower limit of detection (0.055 mm), and the use of a density separator. These findings underscore the necessity for standardised methodologies in microplastic analysis.

5.2.2 Morphological Features of MPs

Within both water and sediments, a range of five distinct microplastic shape types were identified (fibre, fragment, pellet, beads, and film), and the distribution of these shapes is presented in Table 5.5 and Fig. 5.6. The occurrence of microplastic fibres in the river can likely be attributed to their release via sewage systems, often stemming from domestic laundry activities. Browne *et al*., 2011 estimated more than 1900 fibres per wash cycle from a single garment's laundry in domestic washing machines alone. Fibres are also carried by wind and other non-point sources into aquatic ecosystems (Jiang, 2018). While previous studies have demonstrated the effective removal of a substantial portion of microplastics (up to 99%) from municipal effluents by wastewater treatment plants the direct discharge of untreated domestic wastewater into water bodies in Ghana remains a significant contributor (Carr et al., 2016), possibly explaining the heightened presence of fibres in both water and sediment samples (Ntajal et al., 2022).

In some instances, many fibres identified solely through visual assessment (Lenz *et al*., 2015) as microplastics were revealed to be non-plastic materials (Song *et al*., 2015), including natural occurring fibres. In the current study, cellulose accounted for 19% of the polymers found. While cellulose fibres pose a direct environmental risk (Paeriyasamy, 2023), in that their potential harm lies in the presence of associated dyes or additives.

In surface water, the observation of fragment, pellet, and film microplastics was limited to specific sampling mediums. For instance, the proportion of fragment microplastics in sediments (32.2%) significantly surpassed that in surface water (7.4%). The fragment-shaped microplastics are more likely to sink into sediments than their fibre-shaped counterparts. Moreover, the higher average weight of fragments contributes to their sedimentation, unlike the lightweight fibres that remain suspended in surface water, thus accounting for the elevated fibre counts in such surface water (Yuan., 2022). Film microplastics also exhibited widespread occurrence, identified in urban, industrial, periurban, and rural samples. Furthermore, based on visible analysis, a notable number of film microplastics were transparent or white, whereas fragment microplastics tended to be coloured, in alignment with findings by Han et al. (2020).

The predominant colours observed for MPs were black, white, red and transparent. Black and transparent MPs averagely were the most observed in surface water (66.7 % and 14.4%), and black and white were more in sediments (47.6% and 12.2%). The results of MPs colour distribution are summarised in Table 5.5 and Fig. 5.6 4. This colour distribution can be rationalised by considering the manufacturing and usage patterns of some plastic products. Transparent and white colours are commonly associated with disposable tableware, packaging bags, and containers (Su *et al.*, 2016).

Additionally, black-coloured single-use plastic bags are dominant in Ghana. Moreover, the sampling locations could also contribute to the observed colour dominance. Sampling was conducted on high-traffic bridges, which might introduce black-coloured fragments from tire wear into the water bodies. Furthermore, highly polluted water at specific sampling sites might lead to the discolouration of MPs, resulting in a black appearance.

The limited detection of coloured MPs might be attributed to long exposure to ultra violet light which causes fading of colour during the fragmentation or ageing process. For example, some blue and red MPs appeared notably lighter along their edges when compared to their centre (Jian et al., 2020). Additionally, bleaching or fading of MPs may be due to the procedures involved in sample extraction, such as sample digestion. Consequently, the possible reason for increased number of transparent MPs observed in water may be due to over estimation, given the potential influence of fading or bleaching processes (Liu *et al.*, 2022).

Microplastics abundance at each sampling site for size distributions in surface water and sediments along the Odaw River is shown in Fig. 5.6 and Table 5.5. An estimated 75.3% of the observed MPs were ranging in size from 500-3000µm. This size distribution pattern appeared consistent across different locations and seasons. The prominence of this size range in the environment could be credited to the fragmentation of larger MPs through exposure to Ultra Violet radiation or organisms consuming MPs (Dawson *et al.*, 2018). Furthermore, studies have reported that most MPs discharged from wastewater fall within the size category of < 1000 µm (Mason *et al.*, 2016).

Predominant size range of MPs for surface water and sediments was 1000 µm and 3000 µm, accounting for 45% and 46.7%, respectively, with larger MPs being more frequently found in sediment samples. Similar findings were reported, suggesting that smaller MPs are more likely to be carried away by runoff or can be overlooked in the lab analysis process (Hurley & Nizzetto 2018); Zuo *et al.*, 2020). A minor proportion of the identified MPs constituted macroplastics (≥5 mm), making up only 4% of counted MPs. The abundance of relatively large microplastic particles (1000-3000 um) is likely because these MPs experienced long environmental retention times (Haberstroh *et al.*, 2021). Hence, an increased fraction of the MPs was minimally exposed to fragmentation, suggesting that this phenomenon may occur later along the pathway of the MP.

Polypropylene (PP) emerged as the most prevalent type of microplastic, constituting 47% of the total, followed by polyethylene (PE) at 37% and polystyrene (PS) at 16%. These polymers dominate plastics production, accounting for 48.5% of plastic demand (PlasticsEurope, 2019). Their inherent characteristics such as resistance to degradation and widespread use contribute to their extensive distribution within aquatic systems (Klein *et al.*, 2015). Identifying the specific polymer types is a valuable approach that can yield crucial insights (Li *et al.*, 2021). However, discerning the exact environmental origins of these microplastics proves challenging, given their likely origin from non-point sources.

The density of microplastics plays a pivotal role in their vertical distribution within the water column. Research has shown that MPs with low density tend to decline with increasing water depth, while high-density variants exhibit the contrary trend (Li *et al.*, 2021; Mao *et al.*, 2020). Some MPs which are low density like Polypropylene (PP) and

Polyethylene (PE) range from 0.9 to 0.92 g/cm³ and 0.910 to 0.9708 g/cm³, respectively. Consequently, they tend to float near the water's surface, explaining their abundant presence in water samples in the current study. These two polymers are commonly used to manufacture various non-fibre items, including, agricultural films, packaging materials, automotive components, and toys (Geyer *et al*., 2017).

Polystyrene, also a low-density microplastic, finds application in producing disposable products such as building insulation, fridge inner liners, and electrical components (Liu *et al*., 2022). While not immediately discarded, they eventually find their way into the environment at the end of their lifespan. The predominance of these three polymers may likely stem from the commercial and industrial activities along the Odaw River. Moreover, Agbogbloshie, a significant e-waste hub, could contribute to the prevalence of these polymers. The dismantling and scavenging of electronics for valuable components at Agbogbloshie often leads to the destruction or breakdown of plastic parts, introducing these polymers into the environment.

5.2.3 Ecological Risk Assessment

5.2.3.1 Pollution Load Index (PLI)

According to the calculated PLI (Table 5. 7), most sites and zones are highly polluted (risk category: III) for water and sediment samples. Three sites were extremely highly polluted (risk category IV), with two of these sites being from water samples and one in sediment samples. In the dry season, the PLI for the three zones (industrial/ commercial, urban residential and agriculture and periurban/rural) were considered moderately polluted (risk category II) concerning sediment samples. Water samples for all zones in the dry and wet seasons were highly polluted (risk category III). In contrast, the results of risk assessment in sediments presented disparities.

In contrast, the risk assessment outcome in sediments presented notable disparities. The PLI values shed light on the extent of microplastic accumulation within the investigated regions. Consequently, relying solely on evaluating MP concentration in surface water or sediment could lead to underestimating or overestimating the risk associated with microplastic exposure. From the PLI evaluation of MPs in surface water and sediment, all areas had high MPs pollution levels. This observation suggests that the sources of microplastics in the environment may not be limited solely to point sources like industries and domestic wastewater; instead, non-point sources such as atmospheric deposition, runoff, and agricultural activities could also contribute significantly (Deng *et al.*, 2020). Consequently, it is advisable to thoroughly monitor the various sources responsible for microplastic release to mitigate microplastic pollution effectively (Osman et al., 2023).

As the increase in MP risk is commonly credited to intensified human activities, it appears logical to anticipate that urban regions, characterised by higher population density and economic development, would exhibit elevated levels of MP pollution compared to periurban or rural areas. However, the Pollution Load Index (PLI) outcomes reveal a notable similarity in MPs pollution levels across all zones, particularly during the wet season, both in surface water and sediment. These widespread high pollution level suggests a distribution pattern influenced by variations and intensity of water flow in the Odaw River. Consequently, it is possible that MPs could be transported from urban or industrial sources to other areas, e.g., estuary or from remote areas with limited human activities and sparse industries to the highly populated areas where it accumulates. This observation is consistent with the findings of Allen *et al.*, 2019, who suggest that MPs can indeed reach and impact remote and sparsely inhabited regions.

Furthermore, the estuary area emerges as an area of extreme risk for MP pollution in sediments as it has high concentrations of MPs. Some studies have shown that microplastic particles (MPs) tend to accumulate in higher quantities in surface sediments compared to the water column in estuarine environments (Gray *et al*., 2018; Wu *et al*., 2020a). These sediments are thought to act as sinks for MPs (Sánchez-Hernández *et al*., 2021)., hindering their transport from rivers to oceans (Bermúdez *et al*., 2021). However, it's unclear whether this sink is permanent or temporary (Anderson *et al*., 2018). Several factors affect the deposit of MPs in river estuaries, including particle density (Zhou *et al*., 2021), water flow rate (Díaz-Jaramillo *et* al., 2021), proximity to human activities (Díaz-Jaramillo *et al*., 2021), and particle shape (Horton and Dixon, 2018). High-density MPs like PVC sink naturally, while low water flow enhances deposition due to reduced turbulence. Estuarine sediments near industrial and tourist areas are more prone to high MP input. The shape of MPs also influences their settling behavior, with irregularly shaped particles having more complex sedimentation patterns (Malli *et al*., 2022)

In this region, MPs accumulation within sediments reaches significant levels, aligning with the notion that MPs can traverse from upstream to downstream through water flow and subsequently become embedded in sediment due to sedimentation processes and adsorption behaviour (He *et al*., 2021). Moreover, the distribution of microplastics (MPs) in the water may be affected by tidal fluctuations. For example, studies suggest that MPs are carried out of the estuary during ebb tides, and they may re-enter during flood tides, only to exit again during the subsequent ebb tide (Oo *et al*., 2021). This intricate interaction contributes to the high concentration of MPs within the estuary region, especially in the vicinity of the river mouth.

5.2.3.2 Polymer Risk Index (H)

The risk index (H) and corresponding risk categories for each polymer detected in water and sediment samples from the Odaw River are summarised in Table 5.7. Risk assessment for both water and sediments categorise the Odaw River as experiencing an extremely high level of pollution. Despite polystyrene (PS), polypropylene (PP), and polyethylene (PE) being the most prevalent types of microplastics in the aquatic environment, polyester emerges as one of the most hazardous polymers upon exposure to water. Interaction with these polymers through processes like ingestion or inhalation raises the potential for increased risk of pathologies, including lung, tracheal, and lymphatic diseases (Agarwal *et al*., 1991; Xu *et al*., 2010). Furthermore, these polymers have the potential to release toxic additives or monomers, such as dibenzodioxins and dibenzofurans, when weathered or exposed to sunlight, thereby posing additional risks to both humans and aquatic organisms (Bhatt *et al*., 2021; Ma *et al*., 2020). Other polymer types like cellulose, while not inherently considered of primary environmental concern, can potentially contribute to environmental threats through indirect pathways (Hahn *et al*., 2023). When exposed to other harmful additives released by hazardous polymers into the environment, cellulose and similar materials may act as carriers or facilitators of the growth and transport for these additives (Andrady *et al*., 2021). This phenomenon underscores the interconnected nature of environmental pollutants and the potential for interactions that lead to unforeseen consequences.

The diverse toxicities exhibited by different polymers of MPs in the environment arise from their distinct characteristics, physical and chemical properties, and behaviours within the environment. Notably, it is observed that regions with low microplastic pollution loads can still present elevated risks associated with specific microplastic types (Liu *et al*., 2022). For instance, when assessing risk through the Pollution Load

Index (PLI) scores in surface water, particular areas, like the Brekusu source, exhibit relatively low-risk levels of microplastic pollution during the dry season. However, if evaluated using Hazard (H) scores, the same site may be considered at high risk if the polymers present possess high hazard scores. This highlights that the risk of microplastic pollution is influenced not only by the concentration of microplastics but also by the hazardous nature of the specific polymer types.

Hence, a comprehensive evaluation of ecological risk stemming from microplastic pollution necessitates the consideration of both polymer types and their associated hazards, in addition to the concentration of microplastics (Z. Li *et al.*, 2022). This multifaceted approach is crucial to understand better and manage the complex impacts of microplastic pollution on the environment and human health.

5.3 Interactions of Heavy Metals, Microplastics and Sediments

5.3.1 Heavy Metals Concentrations

Heavy metals (Pb, Cu, Fe, Zn, Cr, Hg) were detected in the sediments and meso/ microplastics in the Odaw River. These findings align with the results of other studies conducted at the electronic waste (e-waste) site along the Korle Lagoon, including research by Fosu-Mensah et al. (2017), Vaccari et al., (2019), Ackah (2019), Cao et al., (2020), and Dodd (2023). These studies identified heavy metals in the soils at various locations along the Korle Lagoon. Notably, the concentrations of heavy metals found in the sediments of the Odaw River were lower than those found in the soils at the e-waste sites at the Korle Lagoon (Cao et al., 2020). Consequently, the levels of heavy metals found in the sediments of the Odaw River were relatively lower in concentration compared to those observed in the exposed soil at the e-waste sites.

The presence of heavy metals on the surfaces of meso/microplastics is consistent with the observations made by Antunes et al. (2013), who noted that aged microplastics tend to adsorb more heavy metals. Ashton et al. (2010) also demonstrated that heavy metals, including Zn, Pb, Cu, and Ag, can be adsorbed onto the surfaces of microplastics. Similar results were obtained by Wang et al. (2017) in their analysis of microplastics in sediment along the Beijiang River, where they detected five heavy metals: Ni, Cd, Pb, Cu, and Zn. Other heavy metals such as Cr, Zn, Pb, Ni, and Cd, were also detected on the surface of microplastics.

In addition, it is worth noting that, with the exception of iron (Fe), the meso/microplastic particles exhibited higher levels of heavy metals (including Pb, Cu, Zn, Cr, and Hg) compared to their corresponding sediment samples at all study sites. These findings differ from other studies in which the average content of heavy metals like Cr, Pb, Ag, Sb, Cu, Hg, Fe, and Mn in sediments was higher than that in microplastic particles (Dobaradaran et al., 2018; Wang et al., 2017; Deng et al., 2020; Weber et al., 2022; Zhou et al., 2019).

Regarding the behavior of heavy metals in this context, it's important to recognize that they can either be released from plastics into the environment or be adsorbed by microplastics from their surroundings, including sediments. Previous research in both aquatic and terrestrial settings has documented these two processes—the adsorption of metals from the surrounding environmental medium and the release of additive metals (Holmes et al., 2012). The adsorption mechanisms of microplastics involve alterations to their surface through the presence of attached organic matter (Turner and Holmes, 2015). This organic matter is known for forming water-soluble and water-insoluble complexes with metal ions and hydrous oxides, as well as interacting with silt and clay, which can serve as repositories for metal accumulation (Allen, 2002). Cations or complexes, in this context, would interact directly with charged sites or neutral regions on the surface of microplastics. and co-precipitate with or adsorb onto hydrous oxides (Ashton *et al*., 2010).

In contrast to plastics, heavy metals are natural components of river and floodplain sediments, reflecting their geogenic and intrinsic background levels (Bridge, 2003; Weber et al., 2022). However, it's worth noting that heavy metals have also been entering the environment for an extended period, primarily through human activities, including mining and industrial processes, whereas the introduction of plastics is a relatively recent phenomenon (Zalasiewicz, 2016).

Both heavy metals and plastics share the characteristic of being able to enter the environment from various points within the catchment area. Concerning the environmental and landscape characteristics of the Odaw River catchment, heavy metals can originate from diverse sources. Urban areas, particularly the discharge of urban wastewater from industries and residences, as well as factors related to traffic such as tire and brake wear, have the potential to release both types of contaminants into the environment.

Moreover, heavy metals can also originate within the plastic particles themselves, as demonstrated by Weber et al. (2022). Their study revealed the presence of all heavy metals in the macroplastic and coarse microplastic particles examined prior to their introduction into the environment. These metals are typically incorporated during the plastic manufacturing processes, where they serve as catalysts, pigments, or stabilizers, as indicated by previous research (Wager et al., 2011; Fries et al., 2013; Monica et al., 2010) Although the multitude of additives used in plastic production makes it challenging to pinpoint their specific origins, it is conceivable that certain concentrations identified in the results may arise from these additives. The relatively elevated levels of zinc (Zn) may potentially be associated with the presence of inorganic flame retardants or slip agents (Hahladakis et al., 2018). However, it's important to acknowledge that drawing definitive conclusions about the adsorption of heavy metals onto plastic particles is challenging due to methodological limitations imposed by the digestion method used in this study. The presence of heavy metals in the surrounding sediment matrix from which the plastic particles were extracted could enable adsorption processes. Previous research has indicated that adsorption onto microplastics (MPs) is specific to particular metals, depends on their concentration, and is facilitated by the deteriorated surfaces of the particles (Verla et al., 2019). The accumulation of plastic within the sediments, along with the presence of primarily degraded or highly weathered plastic particles, could promote the release of heavy metals through the degradation of these particles (Verla et al., 2019).

While some studies have suggested that plastic fragments or microplastics could adsorb heavy metals from the environment (Holmes et al., 2012, 2014), the substantial concentrations of heavy metals associated with microplastics in the current study indicate that these heavy metals may not have originated from the sediments. Furthermore, the strong correlation between zinc (Zn), lead (Pb), and copper (Cu) suggests a common source for these metals. These metals are commonly used in the electronics industry, and considering the prevalent dumping of electronic waste (e-waste) in the vicinity of the Odaw River and Korle Lagoon, it is not surprising to find heavy metals associated with microplastics (Osae et al., 2022).

A comprehensive field monitoring study conducted by Rochman et al. (2014) and an earlier investigation by Ashton et al. (2010) revealed that the accumulation of heavy metals in plastic particles was relatively low, typically measuring only a few micrograms per gram (µg/g). Moreover, the concentrations of heavy metals observed in the sediments in the current study were generally lower in comparison. Furthermore, the elevated concentrations of heavy metals associated with meso/microplastics (see Table 5.6) suggest the possibility that microplastics could serve as carriers for heavy metals, and these metals could potentially be transferred from microplastics to sediment. Some researchers propose that metal contaminants exhibit significant correlations with finer particles and total organic carbon (TOC), both of which are known to accumulate in silt and clay due to their higher specific surface area and TOC content (Zhang et al., 2009). Since the sediment in the Odaw River primarily consists of silt and clay, it is less likely for heavy metals to transfer to the microplastics.

The distribution of heavy metals along the Odaw River exhibits spatial variations, with notable differences observed at different sampling points. Agbogbloshie, in particular, consistently showed high levels of heavy metal concentrations. Lead (Pb) concentrations were high at Korle Lagoon, Agbogbloshie, and Haatso. Similarly, chromium (Cr) concentrations were elevated at Christian Village and Agbogbloshie, while copper (Cu) concentrations were high at Agbogbloshie and Korle Lagoon compared to other sampling points. The higher concentration of iron (Fe) in the sediments is attributed to its natural abundance in soils along the Odaw River (Owoade *et al.*, 2021). However, anthropogenic activities along the river may also contribute to its introduction.

The prevalence of high Pb and Cu contents in the sediment samples could be associated with the sampling locations, which were situated along bridges on roads with high vehicular density. Studies have previously reported that areas with well-developed transportation systems tend to exhibit elevated Pb and Cu concentrations in soil (Yu *et al*., 2020).

The downstream section of the river is primarily characterized by a high number of industrial zones. This area plays host to a multitude of industrial establishments, extensive socio-economic activities, and substantial emissions originating from industries, coking plants, and traffic. The results of this study are consistent with this description, as indicated by the Pollution Load Index (PLI) values for these areas, which were notably high, signifying a distressing level of pollution categorized as level IV, indicating an "extremely polluted" condition. This finding corresponds with the conclusions reached by McCormick et al. (2016), whose research demonstrated that certain urban rivers in the United States transport an estimated average of 1,338,757 microplastic pieces per day. Their results underscore the fact that urban rivers exhibit significantly elevated concentrations of microplastics (MPs).

Moving to the midstream section of the river, it encompasses agricultural lands at Haatso and Christian Village. This agricultural presence may contribute to the elevated levels of certain metals detected in this region, with PLI values also indicating an extremely polluted state (PLI == IV). Notably, the spatial distribution of copper (Cu), chromium (Cr), zinc (Zn), and lead (Pb) is primarily concentrated in the downstream and midstream areas, suggesting that industrial, agricultural, and traffic-related activities significantly influence the presence of these metals in the soil.

On the other hand, the portions of the river situated upstream exhibited relatively lower pollution levels, suggesting that the effects of human activities in these regions were less pronounced. This observation is in line with a study conducted by Ma et al. (2016), which identified a noteworthy positive connection between lead (Pb) and zinc (Zn) concentrations in the soil and traffic-related emissions in Changsha. Identifying areas with elevated metal contents highlights the potential impact of industrial, agricultural, and traffic-related activities on metal concentrations in the sediments. These findings emphasize the pressing need to put in place effective environmental management strategies to address metal pollution in the river and protect the ecosystems and local communities. The continuous monitoring and intervention efforts carried out by the Greater Accra Resilient and Integrated Development Project (GARID), funded by the World Bank, are crucial in ensuring the ecological well-being and long-term sustainability of the Odaw River and its surrounding areas.5.3.2 Correlation of Heavy Metals in Sediments and Meso/Microplastics (MMPs).

The relationships between sediment and meso/microplastic elements in the Odaw River are depicted in Tables 5.7 and 5.8, respectively. The Pearson correlation analysis indicates both positive and negative associations among the heavy metals. Notably, there was a correlation exceeding 0.5 between Zn, Pb, Cu, and Zn. However, at a 95% confidence level, the correlation between Zn and Pb was statistically significant, while the correlation between Cu and Pb was not. This alignment in geochemical behavior between Zn and Pb in natural processes (Piehl et al., 2018) could explain the strong correlation, suggesting minimal to no contributions from human activities (Scheurer et al., 2021). Importantly, the concentrations of these heavy metals do not pose any significant environmental concerns. Despite the Odaw River receiving discharges from industries, surface runoff, and domestic waste, the levels of these trace metals are low

(Lechthaler et al., 2021). Therefore, it is likely that the heavy metal concentrations are a result of natural background levels rather than pollution (Weber, 2020). The lack of correlation between some heavy metals (Pb/Fe, Pb/Cr and Fe/ Cu) indicates that a single factor does not control the concentrations of these metals.

The accumulation of heavy metals in the sediments of the shallow waters of the Odaw River may be influenced by organic matter and various physico-chemical properties. The presence of iron and lead in these sediments is linked to the mercury content found in the samples. A notable correlation between different heavy metals suggests that they share common geochemical behaviors and likely originate from similar pollution sources (Corradini et al., 2019). Aside from natural sources, this water body receives heavy metals from various origins, including industrial wastewater containing chemicals, agricultural runoff, and domestic waste.

On the other hand, microplastic (MP) particles contain metals that are incorporated into the synthetic polymer during their production, and these metals can be released into the surrounding environment (Fries et al., 2013; Sighicelli et al., 2018). The study's results reveal a positive correlation in the levels of lead (Pb), copper (Cu), iron (Fe), zinc (Zn), and chromium (Cr) within meso/microplastics. This suggests that the heavy metal content in microplastics is primarily due to their inherent heavy metal content, as some heavy metals, such as zinc, are added to plastics as additives. Plastic polymers are generally considered relatively unreactive with water-soluble metal ions.5.3.3 Ecological Risk Assessment of Sediments

Plastic particles and heavy metals present distinct environmental risks, with plastic contamination being less well-understood than heavy metals. Unlike heavy metals, plastics lack any natural environmental role and are instead foreign, human-made substances that can be found in soil, sediment, or water. Certain metals like iron (Fe), cobalt (Co), copper (Cu), and nickel (Ni) are essential for all living organisms (Alloway, 2013). Nevertheless, elevated concentrations of these metals, particularly when combined with toxic metals such as arsenic (As) and cadmium (Cd), can introduce various potential hazards to ecosystems, organisms, soil functions, and human health (Alloway, 2013). Current methods for assessing the risk associated with heavy metal pollution. in soils involve considering various exposure pathways, durations, potential doses, and national legislation values (Weber *et al*., 2022).

On the contrary, research regarding plastic contamination, particularly in sedimentary environments, is still in its early stages. Consequently, there is a lack of established limit values or legal regulations concerning the maximum permissible levels of plastics in soils. Additionally, while long-term monitoring of heavy metals in soils allows for the determination of geochemical baseline values for comparison, the same cannot be applied to plastic contamination due to its exclusively human-made origin, necessitating a baseline of zero geogenic plastic content in soils (Kabata-Pendias, 2011).

The findings of the current study provide insights into the ecological risk linked to heavy metal contamination in sediment samples from the Odaw River. With the exception of Pollution Load indices, all computed pollution indices (geoaccumulation indices, contamination factor, ecological risk factor, and ecological risk indices) indicate low pollution and low associated risk regarding heavy metals in the sediments.

The study findings reveal high iron (Fe) concentrations in the sediments, ranging from 556.42 to 13362.58 mg/kg. This elevated Fe content could be attributed to its natural abundance in the soil and additional contributions from sources such as vehicle and industrial activities. Despite the high Fe concentrations, the geoaccumulation indices and contamination factor fall below the harm threshold or being considered a pollutant. Hence, the presence of Fe in the sediments does not pose significant environmental risks (Akita *et al.*, 2020).

It is crucial to address the issue of copper (Cu) concentrations, as high concentrations of copper were recorded in Agbogbloshie, although within the permissible range set by the WHO. Copper is essential for human life, but excessive doses can lead to anaemia, liver and kidney damage, stomach and intestinal irritation, and other adverse effects (Taylor *et al.*, 2020). The source of copper at this site may be associated with e-waste activities, such as dismantling copper wires and welding (Ghulam *et al.*, 2023). Therefore, careful regulation is needed to control the introduction of copper into the environment, especially in areas with e-waste activities, to avoid potential health risks associated with human exposure to copper.

Chromium (Cr) is of critical concern as it acts as a toxic, mutagenic, and carcinogenic pollutant when present in soil and water (Taylor *et al.*, 2020). It is commonly used in various alloys, especially stainless steel. Activities like welding, grinding, and polishing stainless steel can introduce chromium into the environment (Tavares *et al.*, 2022). Other sources of Cr exposure include burning fossil fuels and waste incineration. While the Cr levels in sediment samples at all sites may not be potentially harmful, precautionary measures should be taken to reduce further introduction of Cr into the river sediments. Authorities must actively inform and educate the public, particularly individuals dealing with e-waste, about the impacts of the chemicals they come into contact with to minimise potential risks.

The concentrations of lead (Pb), copper (Cu), zinc (Zn), chromium (Cr), and mercury (Hg) in the sediment samples were all below the permissible range set by the WHO. This finding contrasts with other studies and suggests that sediment samples within the Odaw River exhibit low metal levels and do not pose any significant risk to the ecosystem (Fosu-Mensah et al, 2017; Vaccari et al., 2019; Ackah, 2019; Cao et al., 2020; Dodd et al., 2023).

Although the Odaw River is commonly regarded as one of the most heavily polluted rivers in Ghana, the results of this study offer a contrasting perspective in terms of heavy metal pollution in sediments. The research findings suggest that, surprisingly, the sediments in the Odaw River exhibit relatively low levels of pollution of heavy metals. This outcome may indicate potential improvements in the river's environmental condition in recent times or that the specific parameters studied in this research do not fully capture the overall extent of pollution in the Odaw River. Further investigations and a broader spectrum of water quality parameters may be necessary to provide a more comprehensive and accurate assessment of the river's environmental health.

In conclusion, the study highlights the importance of ongoing monitoring and awareness efforts to safeguard the health of the Odaw River and its surroundings. By addressing the potential risks associated with heavy metal contamination, authorities can take proactive measures such as effective management of plastic waste and regulating the use of single plastics to protect the environment and human well-being. Additionally, continued research and collaboration between stakeholders are essential to comprehensively understand and manage the impact of heavy metals in this critical waterway.

5.4 Social Interactions of Plastics Use

5.4.1 Consumption Behaviour

According to the study's findings, the socio-demographic factors such as sex, income, occupation and location did not correlate with plastic use. Generally, it is hypothesized that gender plays a key role in plastic use (Nguyen *et al*., 2022). However, this study data did not support this assumption, as there was no significant difference in plastic use between males and females. This finding contradicts the results of a study conducted by Nguyen *et al*., 2022, which found a significant difference in the consumption of single-use plastic products between males and females, with females consuming more single-use plastic products per week.

Earlier research has frequently linked gender with plastic bag use (Makarchev *et al*., 2022; GNPAP, 2021). However, the contrasting result obtained in this study suggests that plastic use is a non-gendered issue. It implies that the consumption of plastic products is not solely determined by gender but influenced by various other factors such as cultural, societal, and personal preferences. Nevertheless, it is essential to note that even though the findings suggest no significant gender differences in plastic use, gender-inclusive approaches are still crucial in educational initiatives regarding plastic use. It is essential to distribute information and messaging in a way that captures the attention and engagement of both males and females equally. By adopting gender-inclusive strategies, no individual should be left out or underrepresented in efforts to promote sustainable plastic consumption practices.

The consumption of plastic products among respondents was primarily driven by factors such as availability and cost rather than the quality of the products. This aligns with the observation that respondents often accepted plastic bags from shops because they were offered for free. It suggests that the decision to use plastic products is primarily influenced by convenience and economic considerations rather than sustainability or environmental impact. Furthermore, the use of plastics was found to be widespread across various types of plastic products. However, single-use plastic bags emerged as the most commonly used type of plastic across all socio-demographic groups studied. The primary consumers of single-use plastic bags were found among students and self-employed individuals. This trend can be attributed to the fact that respondents within these demographic groups engage in activities, leading to a higher likelihood of purchasing food items in single use plastics. These findings highlight the need for targeted interventions to address these groups' excessive consumption of single-use plastic products.

Cluster analysis of consumers of single-use plastic products revealed the existence of two distinct groups: '*Abstainers*' and 'A*dvocates*'. The observed results suggest that the respondents in the surveyed regions exhibit notable differences in their plastic usage, highlighting the importance of recognizing and accommodating this diversity. Consequently, it becomes imperative to customize intervention and policy strategies aimed at reducing single-use plastic consumption to align with specific attitudinal and behavioral changes related to SUPs. Historically, policies and interventions designed to decrease the use of single-use plastics have operated under the assumption that the general population holds uniform attitudes toward plastic consumption. However, these results support the conclusions of Adam et al. (2021), who propose that a one-size-fits-all approach may not effectively address the various variations in attitudes and behaviors within the population. It is crucial to recognise that individuals have unique reactions and attitudes towards environmental issues (Dikgang and Visser, 2012; Sharma and Bansal, 2013). From an environmental psychology perspective, these findings support the notion that individuals may exhibit diverse attitudes and behaviours towards the same environmental issue (Allison *et al.*, 2022).

The two identified groups, *Abstainers* and *Advocate* users, represent distinct behavioural patterns among respondents towards plastic use. These groups reflect the extremes in attitudes and behaviours related to (SUPs). The *abstainers,* situated at one extreme, exhibit unfavourable attitudes towards SUPs. They acknowledge and believe that SUPs pose environmental problems. These individuals actively demonstrate their beliefs through their actions. They actively avoid using SUPs whenever possible, even when offered for free. They opt for reusable alternatives and often carry their bags for shopping. This group aligns their behaviour with their anti-SUP attitudes and can be seen as advocates for sustainable practices. Conversely, the *advocate users* exhibit behaviours that support using SUPs despite being aware of their impact on human health and the environment. For this group, convenience and affordability outweigh concerns about environmental impact. They readily accept and use SUPs, even when offered alternatives. They are unwilling to pay extra for reusable alternatives and do not actively seek sustainable options. This group represents the patrons of SUPs, whose preference for plastics may be as result of the convenience and cost-effectiveness of using SUP or may be as a result of the lack of alternatives.

The variations in socio-demographic characteristics among the identified groups although were not significant, further highlight the influence of background factors on individuals' behaviours towards SUPs. It is well-established that attitudes are shaped through socialisation, and an individual's background, including age, educational level, occupation, income, and location, can significantly impact their attitudes and subsequent behaviours (Adam *et al.*, 2021). As part of the process of socialisation, societal expectations impose specific norms and values that can shape individuals' behavior, depending on their underlying characteristics. (Adam, 2021).

Although the overall number of pro-plastic users was higher than that of pro-environmentalists, significant differences were observed in only two socio-demographic factors measured education and occupation. As noted by Adam *et al*, 2021, individuals with higher educational levels would be expected to have better knowledge and understanding of the threats posed by SUP waste and, therefore, use fewer plastic products. However, this study revealed that respondents across all educational levels, including those with no academic background, were pro-plastic users. On the other hand, there were relatively higher numbers of pro-environmentalists among those with secondary-level education. This could be attributed to the fact that in recent times, primary and secondary-level education curricula incorporate lessons on environmental issues, making students more aware of their environmental responsibilities at this level. Additionally, the presence of environmental clubs in schools also helps shape students' behaviour in environmental management.

These results align with the research carried out by Adam et al. (2021), which similarly observed that individuals with higher levels of education tend to avoid plastic products. This contrasts with other studies in the field of attitudes and behaviors related to plastic usage, as seen in the works of Adam *et al.*, (2021), Amoah and Addoah (2021), and Erhabor and Don (2016). the current study only found significant influences in education and occupation on the behaviour of respondents, other socio-demographic factors did not have significant influence on attitudes and behaviours towards plastic use. In certain societies, the attitudes towards plastic usage may not be notably swayed by an individual's age, gender, or occupation, since prevailing cultural norms tend to exert a more pronounced influence on behavior (Gu et al., 2023). For instance, if a culture highly values environmental conservation, individuals of all ages and backgrounds may be inclined to reduce their plastic consumption, regardless of their demographic characteristics. Conversely, in cultures where convenience and disposability are prioritized, individuals may continue to use plastic regardless of their age or occupation. Moreover, when there are scarce substitutes for plastic in a specific context, people from diverse age groups, genders, and occupational backgrounds could find themselves equally restricted in their options (Northen *et al.*, 2023). Furthermore, the presence and convenience of alternative materials can differ, creating hurdles for age, gender, or occupation to significantly affect behavior when people have few alternatives to choose from.

5.4.2 Plastic Waste Management

In plastic waste management, recycling is widely recognised as a key solution to reducing plastic waste and promoting sustainable use of plastics (Zhuang *et al.*, 2008). By enhancing waste separation practices, the quality of recyclables can be improved, leading to more efficient and effective recycling processes. The study explicitly investigates respondents' waste separation and recycling activities along the Odaw River. The results revealed that a significant proportion of respondents, approximately 56%, do not engage in plastic waste separation practices (separating plastics from other waste). Furthermore, a corresponding 58% of respondents do not recycle their plastic waste.

The reasons provided by respondents for not separating and recycling their plastic waste were informative. The majority of respondents, 63.4%, stated that it was easier to dispose of their plastic waste than going through the recycling process. This highlights the importance of convenience and ease of disposal in influencing individuals' waste management behaviours. Additionally, 22% of respondents expressed that they were not bothered about recycling, suggesting a lack of motivation or awareness regarding the benefits of recycling.

Despite the general agreement among respondents about the importance of recycling, most did not engage in recycling practices. This discrepancy between attitudes and behaviours highlights the need for targeted interventions that bridge the gap between intention and action. This is consistent with the findings of a study conducted by Kombiok and Jaaga (2022) in the Tamale metropolis, which concluded that although there was a high level of knowledge regarding the disposal of plastic waste, the practical implementation of this knowledge was low. This supports the widely held notion that individuals' attitudes play a significant role in the challenges faced in addressing plastic pollution globally (Allison *et al.*, 2022)

Similarly, McAllister (2015) discovered that despite the awareness among citizens of Gaborone, Botswana, regarding sustainable waste management techniques such as recycling, this awareness does not necessarily translate into a willingness to actively engage in pro-environmental activities like recycling initiatives. Asase *et al*. (2009) propose that overcoming the waste crisis requires raising environmental awareness, promoting sustainable consumption practices, educating individuals on plastic waste management, and developing and enforcing laws and regulations related to plastic waste management.

Addressing barriers such as convenience, awareness, and motivation is crucial to promote waste separation and recycling effectively (Thompson *et al.*, 2009). Interventions should focus on providing accessible and convenient recycling facilities, raising awareness about the environmental benefits of recycling, and emphasising individual contributions towards mitigating plastic waste pollution. Education campaigns and community engagement initiatives can also significantly promote behavioural change and foster a culture of waste separation and recycling (Kumar *et al.*, 2021). Collaboration with traditional leaders and other community stakeholders on the ways to mitigate the excess use of plastics will help in the success of the implementation process.

Socio-demographic factors did not emerge as significant predictors of waste separation or recycling practices among the respondents. However, the location of the respondents played a crucial role in determining their preferences for plastic waste management. In particular, respondents from Old Fadama exhibited a higher tendency to hand their waste over to waste collectors, with 70% adopting this practice. This can be attributed to the highly organised closed community (slum) in Old Fadama, where community leaders enforce strict waste disposal regulations, limiting options for handing waste over to collectors. Open dumping and burning are discouraged in this community due to previous fire outbreaks and property damage. Although open dumping was not observed within the community, there were instances of open dumping in surrounding areas.

On the other hand, the community of Brekusu had the highest percentage of respondents opting for burning as a disposal method, accounting for 63% of responses. This preference for burning can be attributed to the practice of using single-use plastic bags as fuel for cooking. Respondents in Brekusu mentioned utilising these bags as a substitute fuel source instead of using kerosene to fire their charcoal or wood fuel when cooking.

The specific waste management practices observed in Old Fadama and Brekusu highlight the impact of community norms and cultural practices on plastic waste management preferences. These findings suggest the need for tailored interventions considering different locations' unique characteristics and traditions when designing waste management strategies.

Plastic management has become an urgent concern for governments worldwide, given its detrimental environmental and human health impact. This study examines two prominent general management options for plastic waste: implementing a ban on single-use plastics and introducing a payment system for reusable alternatives. The study found that 62% of respondents disapproved of a ban on single-use plastics and the payment system for reusable options. These results indicate a noteworthy division in public opinion regarding addressing plastic waste management through regulatory measures.

A primary reason cited by respondents who disagreed with a ban or payment for reusable alternatives was the fear that retailers of single-use plastic products would suffer economically. The respondents raised concerns that implementing such measures would lead to job losses and potentially put these businesses out of operation. As a result, there is a call for an alternative business option that would support affected retailers during the transition. To address the concerns raised by the respondents, the government needs to seek sustainable business solutions before implementing any ban on single-use plastics. By involving stakeholders in the process and creating opportunities for retailers to adopt and promote reusable alternatives, a smoother transition can be achieved without causing significant disruptions to the market. In the case of Rwanda's plastic bag ban, there was a lack of extensive consultation with stakeholders and no evident progress in improving the accessibility of recycling technologies or alternative materials. Consequently, individuals began importing plastic bags from neighboring countries (UNEP, 2018)

Secondly, respondents highlighted the cost of reusable alternatives. Single-use plastics have been widely used due to their affordability. For any payment system for reusable alternatives to be effective, it must ensure that the cost of these alternatives is competitive and accessible to the general public.

These results and concerns raised by respondents agrees with: Babayemi *et al*., 2019: Adam *et al*., 2021; Deme *et al*., 2022 who identified significant challenges in the management of microplastics in Africa. While many African countries have taken steps like prohibiting single-use plastic bags, the studies emphasize a number of key issues. Firstly, they assert that bans on single-use plastics have not yielded the desired impact, mainly because they have not been widely embraced by consumers or businesses. Secondly, there is a notable lack of collaboration between the public and private sectors, hindering the effective implementation of waste management strategies. Thirdly, there is a deficiency in price and regulatory mechanisms to incentivize changes in waste disposal habits. In simpler terms, plastics remain the preferred option due to their affordability and convenience.

5.4.3 Risk Perception

The results of this study reveal that a substantial portion of the participants (80%) possessed a strong comprehension of the environmental repercussions of plastics. These outcomes are consistent with previous research, as demonstrated by Dilkes-Hoffman *et al*. (2019), who found that more than 70% of their respondents concurred that plastics were responsible for significant environmental problems, including marine pollution, biodiversity depletion, waste disposal challenges, and air and water pollution. Similarly, studies conducted by Van Rensburg et al. (2020) conducted a study with Durban beachgoers in South Africa, while Charlebois et al. (2019) surveyed Canadian consumers. Both studies reported that a high percentage of their respondents, 90% and 87.2% respectively, acknowledged the harmful environmental impact of single-use plastics (SUPs). Furthermore, Rhein and Schmid (2020) investigated the awareness of German consumers regarding plastic packaging materials and found that a significant majority of consumers were cognizant of the substantial environmental problems associated with these materials. These consistent findings across different studies and contexts highlight the widespread awareness among the public regarding the detrimental environmental impacts of plastics. It signifies the growing recognition of the need to address plastic pollution, implement measures to reduce plastic consumption and promote more sustainable alternatives.

Age and educational level were two socio-demographic characteristics that influenced respondents' perceptions and responses regarding plastic use and its associated threats. Specifically, these findings suggest that education plays a significant role in shaping individuals' perceptions of plastic as a threat. It is widely recognised that individuals with higher levels of education tend to a deeper understanding of environmental issues and are more inclined to embrace sustainable behaviors, (Haron *et al*., 2005; Van Rensburg *et al*., 2020).

Although the majority of respondents in this study demonstrated awareness of the impacts of plastics on human health and the environment, this awareness did not significantly impact their actual use of plastics. This discrepancy suggests that while knowledge and awareness are crucial factors in promoting environmentally friendly behaviours, they may not necessarily translate into changes in plastic consumption practices. These findings highlight the complexity of individuals' behaviours and decision-making processes regarding plastic use. It implies that factors beyond awareness and knowledge, such as convenience, affordability, and social norms, may also significantly shape individuals' behaviours towards plastics.

To effectively reduce plastic consumption, it is important to consider a multifaceted approach beyond merely providing information and raising awareness. Strategies and interventions should address various influencing factors and barriers to behaviour change, considering educational level and other contextual and psychological factors (Ali et al., 2022).

Respondents identified several major impacts of plastics. The most frequently mentioned impacts included clogging drains, contributing to a dirty city environment, and causing diseases in humans. These responses are particularly relevant to the respondents living along the Odaw River, as they experience annual flooding due to clogged drains. Therefore, the issue of clogged drains resulting from plastic waste was of concern to them. In addition to the practical consequences of clogged drains, respondents also emphasized the aesthetic aspect of plastic waste. They expressed that plastic waste contributes to the visual pollution of the city, negatively impacting its appearance. This indicates that respondents consider the presence of plastic waste as displeasing and detrimental to the overall aesthetics of their surroundings.

These findings highlight the tangible and visible impacts of plastics on the local environment and the respondents' daily lives. The detrimental effects on drainage systems and the visual pollution caused by plastic waste are directly experienced by the community living along the Odaw River.

5.4.4 Knowledge of MPs

To tackle the problem of microplastics, it is essential to take into account the human dimension. (Zhang *et al*., 2012). It is important to understand the public's perception of microplastics. This is because the public's perception, decisions, and actions play a pivotal role in tackling the problem of microplastics in the environment (Pahl and Wyles, 2017). The knowledge of microplastics among the respondents was extremely low, with only 12% indicating prior awareness of the term "microplastics" before the survey. Most respondents (88%) had never heard of microplastics, suggesting a significant gap between academic research on microplastics and public awareness. This highlights the challenge of translating scientific knowledge into widely understood concepts among the general population (Adam et al., 2021) . Moreover, approximately 90% of the respondents did not understand the impacts of microplastics on human health and the environment.

During the survey, respondents received a brief education on microplastics, including their sources, characteristics, and potential effects on human health and the environment. Some respondents mentioned hearing about microplastics from their school, while others made guesses based on their limited knowledge. This indicates a lack of accessible information on microplastics, and the sources of information are limited. It suggests that the issue of microplastics has not yet garnered sufficient attention from the government and the public, leading to a lack of awareness and understanding among the population.

Although research on microplastics in Ghana is still in its early stages, it is crucial to continue and expand such investigations. An increased focus on research will yield a more in-depth understanding of the local microplastic pollution situation and its precise consequences on the environment and human well-being.

These findings underscore the importance of promoting the publicity and education of relevant knowledge on microplastics in future policy-making. There is a need to bridge the gap between academic research and public awareness by developing comprehensive and targeted educational campaigns that effectively communicate the risks and impacts of microplastics to the general population. This will require collaboration between researchers, policymakers, and relevant stakeholders to ensure that information on microplastics is widely disseminated and understood, ultimately leading to informed decision-making and the implementation of effective policies to mitigate the impacts of microplastics on the environment and human health (Deng, 2020).

Information dissemination through various mediums, including media outlets and educational institutions, is indispensable to bridge the knowledge gap. Television, radio, newspapers, and online platforms can serve as effective channels to reach a wider audience. Integrating microplastics and environmental topics into school curricula can also help promote pro-environmental behaviour.

Beyond media and schools, engaging other information mediums, such as community workshops, seminars, and social media campaigns, can enhance the reach and impact of awareness initiatives. Collaboration with local environmental organisations and governmental agencies can further amplify the dissemination efforts.

5.4.5 Structural Equation Model

The objective of this study was to study the relationships between the latent factors of Plastic use behaviour (PUB), Plastic waste management (PWM), Risk perception of plastics (RIP), and knowledge of microplastics (KMP). Confirmatory factor analysis was used to assess the model fit, and overall, the model demonstrated a good fit for the data. However, it should be noted that there were some estimates of the observed variables that fell below the accepted values, specifically for RIP2, RIP1, PWM3, and PUB1.

Among the observed relationships, significant associations were found between plastic waste management (PWM) and risk perception of plastics (RIP), as well as between Plastic use behaviour (PUB) and Plastic waste management (PWM). These significant relationships indicate that when examining plastic use behaviour, both risk perception of plastics and plastic waste management are essential factors to consider. These findings have important implications for policy-making and interventions promoting sustainable plastic consumption.

It is evident that in order to address plastic use behaviour effectively, efforts should be directed towards enhancing individuals' risk perception of plastics and promoting proper waste management practices. By increasing awareness and understanding of the risks associated with plastic consumption and encouraging responsible waste management, policymakers and practitioners can develop more targeted strategies to promote sustainable behaviours and reduce the environmental impact of plastic waste (Ali et al., 2022).

Overall, the findings of this model show the importance of considering the interplay between risk perception, waste management, knowledge of microplastics and plastic use behavior. By incorporating these factors into policy-making and interventions, it is possible to foster a more sustainable approach to plastic consumption and contribute to the reduction of plastic pollution.

5.4.6 Implications for Policy

These findings suggest that the results of this study carry significant implications for policy and interventions aimed at reducing plastic consumption and promoting sustainable behaviours.Firstly, the study challenges the assumption that gender plays a significant role in plastic use. The results indicate that plastic use is a non-gendered issue, suggesting that interventions and educational campaigns should adopt a gender-inclusive approach. By ensuring that information and messaging reach and resonate with all individuals, regardless of gender, policymakers can develop more effective strategies to reduce plastic consumption and promote sustainable behaviours.

Secondly, to promote sustainable consumption patterns, it is important to implement measures that effectively regulate the use of single-use plastics. This can involve introducing policies and regulations that discourage the usage of single-use plastics and promoting alternative, more sustainable options. By implementing these measures, policymakers can create a shift in consumer behaviour and incentivise individuals to choose eco-friendly alternatives, leading to a reduction in overall single-use plastic consumption.

Furthermore, the findings highlight the importance of addressing factors such as availability and cost that drive plastic consumption. Policymakers should consider implementing effective regulations, such as levies or bans, to discourage the use of single-use plastics and promote the adoption of reusable alternatives. Additionally, incentivising businesses and individuals to adopt sustainable practices can further encourage reducing plastic consumption. This study underscores the importance of recognising and addressing the heterogeneity in attitudes and behaviours towards plastic use. By tailoring interventions and policies to specific consumers, policymakers can effectively target their efforts and maximise the impact of their initiatives. Ultimately working towards a more environmentally conscious and sustainable future by promoting sustainable behaviours and reducing single-use plastic consumption.

The issue of plastic management demands a comprehensive and multifaceted approach. While a ban on single-use plastics and payment for reusable alternatives may seem like viable solutions, public opinion reflects concerns about the potential impact on businesses and the affordability of alternatives. To achieve an effective and sustainable plastic management strategy, the government must collaborate with various stakeholders to develop business-friendly alternatives and ensure that the transition to reusable alternatives is economically viable and accessible to all citizens. By addressing these concerns, governments can move towards a more eco-friendly and responsible plastic waste management.

Overall, the study emphasises the need for comprehensive and targeted policies that address the various factors (socio-demographic factors, plastics waste management, risk perception of plastics, knowledge of microplastics, education and the implementation and enforcement of rules and regulations to encourage individuals to translate knowledge into action) influencing plastic use. By reducing the consumption of single-use plastics and promoting sustainable alternatives, policymakers can make significant progress in mitigating the environmental impact associated with plastic waste.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter provides summaries of the key conclusions drawn from the study's main findings of the three distinct categories of the specific Objectives (Occurrence, Interactions with heavy metals and Social Interactions), providing a succinct overview of the research outcomes. Additionally, a set of recommended actions and interventions rooted in the conclusions of the study is presented. Additionally, further empirical investigation is proposed to advance the understanding of the subject matter.

6.2 Conclusion

6.2.1 Occurrence of Microplastics

The study addresses the growing concern surrounding microplastic contamination and its consequences in freshwater ecosystems. It specifically focuses on the Odaw River in Ghana, which has received limited attention in microplastic investigation. The research investigates the presence, distribution, and potential risks associated with microplastic pollution in the Odaw River, highlighting its proximity to various human activities and land uses. The study reveals that MPs are prevalent in both water and sediment in the Odaw River, indicating a significant impact from anthropogenic factors. The main characteristics of the microplastics studied were black colour (water: 66.7%, sediments: 47.6%), fibre, shape (73.4%), size 1000-3000 µm (water: 45.0% and sediments: 46.7%) and PE polymer type (48%). These characteristics of MPs could indicate that mainly secondary MPs are in the Odaw River and may originate from clothing and disposable single-use plastics, the predominant plastic used by residents.

The distribution of MPs exhibits distinct variations between wet and dry seasons, closely tied to water flow dynamics. The wet season witnesses heightened accumulation of MPs within both sediments and water, contrasting with the dry season when lower influx and water transport contribute to reduced MPs levels. The modulation of water flow patterns serves as a conduit for the dispersion of MPs across different zones, facilitating their movement from upstream and midstream sources to downstream regions. Notably, the Estuary/Lagoon zone, characterised by less frequent human activity, has significant MPs presence, underscoring the transport role of water in this distribution.

Furthermore, the study conducted a comprehensive risk assessment, considering MP concentrations, polymer types, and toxicity, to enhance understanding of plastic pollution in freshwater ecosystems and underscore the human impact on MP pollution levels in the Odaw River. The findings revealed that industrial/commercial, urban residential, and agriculture zones showed a significant abundance of MPs in both water and sediment, indicating a high-risk level of MP pollution in these areas. This demonstrates the critical role of anthropogenic activities, mainly residential, agricultural, and industrial/commercial, in driving Odaw River's plastic pollution.

The Pollution Load index analysis in all designated zones (Lagoon/Estuary, Industrial/Commercial, Urban Residential/Agriculture, and Periurban/Rural) are high-risk areas for MPs pollution. However, the periurban zone demonstrates a comparatively lower risk profile based on sediment MPs concentrations. Additionally, the widespread distribution of MPs resulted in all zones being highly polluted using the

PLIzone scores. It is imperative to highlight that the risk assessment, considering MPs toxicity, raises concerns about the industrial area's surface water and sediment across all zones, emphasising their potential threat to aquatic ecosystems and human health. Polymer Risk Index (H) also highlights the extremely high pollution of the river by hazardous polymers. The findings underscore the complex interplay between water flow, MPs distribution, and associated risks, contributing valuable insights to understanding MPs' behaviour within the Odaw River.

6.2.2 Interactions with Heavy Metals

The study also shed light on heavy metal concentrations in both sediments and meso/microplastics at seven sampling sites along the Odaw River. The concentrations of heavy metals in meso/microplastics were generally higher than those in sediments, except for iron (Fe) concentrations. It is well-established that plastic particles can adsorb metals from their surroundings or release metal additives that are inherent in them into the immediate environment. The metal content found in meso/microplastics might originate from the additives, such as stabilisers or pigments, added during the production of synthetic polymers.

The findings of this study reveal that meso/microplastics in the soil environment possess different concentrations of heavy metals, with some metal concentration being higher in meso/microplastics compared to the surrounding soils. This suggests that meso/microplastics may act as vectors for transporting heavy metal pollutants into the sediments, or these heavy metals have a high affinity to meso/microplastics than sediments. Consequently, the synergistic pollution of meso/microplastics and heavy metals could pose an ecological risk and potentially adversely impact soil organisms.

Despite the Odaw River being considered one of the country's most contaminated rivers, this study's results indicate that heavy metal pollution in its sediments is relatively low, based on the ecological risk indices calculated. This suggests that while heavy metals are present in the river, their levels are within acceptable limits in sediments along the Odaw River. Nonetheless, ongoing monitoring and research are essential to comprehensively assess the potential risks and implications of heavy metal pollution in the river and its surroundings.

6.2.3 Social Interactions

Generally, the finding of the social interaction study encourages the consideration of factors such as behaviour, risk perception, plastic waste management and knowledge of microplastics in solving the excessive use of plastic products. As indicated by the structural equation modeling which showed that these latent factors were best fit for the model.

Age, education, and occupation all influenced behaviour according to the results of this study. Although gender is seen as a key factor in determining the use of plastics, this study found that plastic use within the respondents studied was non-gendered, thus encouraging equal reach of information to all genders when creating awareness on plastic consumption and sustainability. Plastic use was also informed by availability and cost, showing that with regulations restricting single-use plastics, individuals will have no alternative but to use what is available. Although this may be a choice for managing plastic use, the economic considerations of the populace must also be factored in so that alternative products will not only be available but also be affordable.

The impact of plastics on human health and the environment is critical in informing individuals' risk perception. Respondents were aware of the negative impacts of plastics on the environment and human health, as some had first-hand experience with flooding. Despite the knowledge of the harmful impacts of plastics, especially single-use plastics, most people still use these plastics incessantly. Regarding management options, respondents opposed the notions of a ban on single-use plastics and payment for reusable alternatives. Therefore, a gradual approach to introducing reusable alternatives, supported by business initiatives and cost considerations, appears essential in fostering a positive shift towards more sustainable plastic management practices.

This study shows that knowledge of microplastics and their impacts is generally low among respondents in Ghana, although those with higher educational levels tend to be more aware. This disparity highlights a critical gap in research and public understanding.

6.3 Recommendations

6.3.1 Occurrence

- These findings underscore the importance of implementing comprehensive management strategies to mitigate the pervasive impact of microplastic pollution in various aquatic environments. Thorough monitoring of freshwater ecosystems is needed in Ghana in order to ascertain the impact of plastics to these ecosystems. In addition, data from this monitoring will help in decision making towards the management of microplastics in Ghana’s waters
- Research institutes such as Water Research Institute and other institutions should spearhead future research endeavours to target the point sources of contamination to address microplastics (MPs) management effectively.

Moreover, adopting standardised approaches for sample collection, processing, characterisation, and quantification of MPs is imperative in future research. In addition, in-depth studies to assess microplastics' potential impact and toxicity on aquatic organisms is needed. This knowledge will be instrumental in devising strategies to curtail the abundance of MPs within river ecosystems. For policy implementation, it is paramount to take into account the origins and accumulation points of these microplastics. This holistic approach is essential for formulating measures to purify water bodies and sedimentary environments

- To ensure compliance with plastic reduction goals, monitoring mechanisms need to be established for industrial practices by the Environmental protection Agency of Ghana. This may involve regular assessments, audits, and reporting requirements for industries to track and report their plastic consumption and waste management efforts.
- Collaboration between industries, regulatory agencies, and environmental organizations is key. By working together, they can develop strategies to reduce plastic use and assess the effectiveness of these initiatives over time.
- In order to decrease the release of microplastic fibers from clothing, it is essential to ensure sustainable practices in the import of second-hand clothing. Additionally, importing high-efficiency washing machines can significantly contribute to reducing fiber concentrations in wastewater generated during the washing of clothing.

6.3.2 Interactions with Heavy Metals

- The presence of e-waste materials in the downstream section of the Odaw River may be a contributing factor to the increased concentrations of heavy metals found in sediments, especially on meso/microplastics. To mitigate this issue, it is imperative to implement effective e-waste management practices that involve removing these materials from the vicinity of the water body. The Ministry of Sanitation and Water Resources is to lead the implementation of this action. This action is crucial for reducing heavy metal concentrations in the sediments.

- To minimize the presence of microplastics (MPs) and heavy metal contents in the sediments of the Odaw River, it is essential that the responsible stakeholders, particularly industries located along the river, rigorously adhere to waste treatment processes before discharging their effluents into the river. This compliance is crucial for maintaining the environmental integrity of the river.
- Because certain heavy metals exhibit a strong affinity for microplastics (MPs), it is imperative to mitigate the presence of multiple stressors within the Odaw River to minimize interactions between heavy metals and MPs. Reducing these stressors is essential for safeguarding the river's ecosystem.
- Further studies considering the hydrology, physico-chemical parameters, biofilms, Heavy metals and MPs is encouraged to determine the effects of these pollutants on the aquatic environment.
- The current research on heavy metal (HM) predominantly centers on isolated factors, such as specific characteristics of microplastics (MPs) or sediment physicochemical properties. There is the need to examine how other factors interact to influence HM bioavailability, despite the potential ecological risks associated with such interactions. Therefore, it is imperative to conduct comprehensive research that explores the interactions of multiple factors. Furthermore, investigating the involvement of microorganisms in this process is an area for further investigation.

- Further research is needed for in-depth study into the mechanisms of metal adsorption on meso/microplastic in the aquatic ecosystem and to explore the effects induced by such synergistic pollution.

6.3.3 Social Interactions

Achieving effective plastic use and management necessitates a collaborative endeavor encompassing individuals, communities, businesses, and governments. These recommendations are proposed as effective mitigation measures to pave the way for a plastic conscious future.

- Encouraging individuals to modify their behavior is crucial for reducing the utilization of disposable plastics like plastic bags, cutlery and straws. The role of individuals in curbing plastic consumption is pivotal, as they can actively contribute by consciously reducing their reliance on single-use plastics, practicing responsible recycling, and opting for reusable alternatives. Promoting education and awareness campaigns is a means to help individuals grasp the environmental implications of excessive plastic usage.
- This study has shown that risk awareness does not necessarily translate to effective management of plastic waste hence incentives must be put in place to compel individuals to better manage their plastic waste. The Odaw River has pollution challenges which can be addressed by Government playing a crucial role by enacting legislation that bans waste from being thrown into the river and promotes reduced plastic use and implementing incentives for sustainable practices such as recycling.

- Promote the adoption of reusable alternatives, such as cloth bags and stainless-steel straws, ensuring that they are not only accessible but also cost-effective. This approach has the potential to stimulate shifts in both individual and industry behaviours.
- Consequently, there is a compelling need for effective information dissemination to increase public awareness and promote responsible actions toward microplastic pollution.
- All stakeholders must be involved in the decision-making exercise of either banning plastics or providing cheaper alternative materials.
- The structural equation model employed to assess the connection among the studied factors demonstrated a strong fit. Nevertheless, certain observed variables did not meet the acceptable range of 0.35-0.56, indicating limitations. Therefore, it is advisable to conduct additional research to identify appropriate observed variables that can be incorporated into the model, creating a robust framework for shaping and implementing policies aimed at ensuring the sustainable use of plastics.
- In conclusion, it is essential to take steps to minimize plastic pollution in the environment, regardless of its origin. This commonly expressed request involves both the shift toward a more efficient circular economy and an expanded focus on public relations initiatives.

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APPENDICES

Record Sheet

Microplastics: Field Sampling Record Sheet

Officer/s: ....

Date: ....

Sampling no.: ....

Site name: ....

Start time: ....

Finish time: ....

Site code:

Lat:	Long:

Field measurements

Parameter	**Result**
Temperature (°C)	
Turbidity (NTU)	
Dissolved oxygen (mg/L) (% saturation)	
Electrical conductivity (µS/cm)	
pH	
Salinity (‰)	
Eh (mV)	
Others	

Field observations

Observation	**Details**
Weather (e.g., wind, wind direction, cloud cover):	
Colour and appearance of water	
Water surface condition (odour frothing) Water flow, level, tide:	
Presence of nuisance organisms (e.g., phytoplankton scums, algal mats, grease)?	

Questionnaire

INSTITUTE FOR ENVIRONMENT AND SANITATION STUDIES
UNIVERSITY OF GHANA, LEGON
Microplastics in Freshwater Ecosystems: The Case of Odaw River Basin, Ghana
Knowledge and Risk Perceptions on Microplastics and Plastic Pollution

Introduction

I am Millicent Amekugbe a PhD candidate at the University of Ghana researching microplastics in freshwater environments. The objectives of this survey are to assess the knowledge and perception of individuals on plastic use, plastic waste management and microplastics and their impacts on the environment. This questionnaire is intended to gather the views of the general public on the above topic to contribute to scientific knowledge. Kindly note that your participation in this study is voluntary. It would take less than 20 minutes to fill this form. All responses collected will be regarded as confidential and strictly used for academic purposes.

You do not have to answer any questions or take part in the survey if you feel uncomfortable with the question(s). Remember, your responses will remain anonymous. **There will be no direct benefit to you, however your participation is likely to assist in the understanding of the relationship between people's awareness and attitudes towards plastic consumption.** In case of any questions, comments or clarifications kindly contact: Millicent Amekugbe on Email: maamekugbe@st.ug.edu.gh Mobile Number: 0247168090. Your participation would be greatly appreciated. Thank you for your cooperation.

Socio Demographic Parameters (*Please tick the correct answers where appropriate).*

1. Sex
   - ☐ Male
   - ☐ Female
2. Age
   - ☐ 12-17yrs
   - ☐ 18-24yrs
   - ☐ 25-34yrs
   - ☐ 35-44yrs
   - ☐ 45yrs and above
3. Level of Education
   - ☐ Primary
   - ☐ Secondary
   - ☐ Tertiary
   - ☐ None
4. Occupation
   - ☐ Formal
   - ☐ Self Employed
   - ☐ Informal
   - ☐ Unemployed
   - ☐ Student
5. Income per month (GHC)
   - ☐ <200
   - ☐ 200-500
   - ☐ 500-1000
   - ☐ 1000-5000
   - ☐ >5000

Plastic Use, Behaviour and Attitude

6. Do you use plastic products?
   - ☐ Yes
   - ☐ No
7. Why do you prefer using plastic products? **Check all that apply*

☐ They are light weight ☐ They are easily available

☐ They are cheap ☐ Lack of alternative materials

☐ They are durable ☐ All of the above

8. Which plastic products do you use most often in order of importance (1-5 one being most important and 5 being least important? **Check all that apply.*

Plastic bags ☐

Plastic buckets, bins, barrels, Storage containers ☐

Packaging (bottles, sachets, food container from food delivery, cling wraps, cosmetic containers) ☐

Plastic bottles ☐

Plastic disposables (Straws, plates, spoons etc.) ☐

Other: ______________________________

9. Which type of bags do you prefer for shopping? **Check all that apply.*

Plastic bags ☐

Paper bags ☐

Cloth bags ☐

Other: ☐

10. Do you carry your own bag for shopping? **Mark only one oval.*

☐ Yes ☐ No

☐ Sometimes

11. If Not, why? *Check all that apply.*

☐ I usually forget

☐ I get plastic bag for free

☐ I am not concerned with the type of bag I use for shopping

12. If the shop keeper gives you plastic carry bag, what is your reaction? * Mark only one oval.

☐ Accept it always

☐ Refuse it sometimes

☐ Refuse if having alternative carry bag

Plastic Waste Management

13. Do you reuse/recycle single use plastic carry bags? **Mark only one oval.*

☐ Yes ☐ No

☐ Often ☐ Rarely

14. If yes, how many times do you reuse it? **Mark only one oval.*

☐ Reuse 1-2 times

☐ Reuse 2-5 times

☐ Reuse till end of life, Explain ______________________________

15. If not reused give reason. **Check all that apply*.
    - ☐ Not aware about reuse
    - ☐ Not bothered about these issues
    - ☐ Find disposing easy and better, Other: ______________________________

16. Do you separate plastic waste from other waste products in your house *Mark only one
    - ☐ Yes ☐ No
    - ☐ Sometimes ☐ Not aware of waste separation

17. How do you dispose plastic waste? *Mark only one.
    - ☐ Handover to waste collectors.
    - ☐ Municipal corporation collection bins
    - ☐ Open damping
    - ☐ Burning

18. Do you or your locality tie up with waste recyclers to recycle the plastic waste? *Mark only one
    - ☐ Yes ☐ No

19. Below are some statements. Please indicate the extent to which you agree/disagree with each statement.

	Strongly disagree	*disagree*	*Agree*	*Strongly Agree*
Plastics waste in your locality are well managed	☐	☐	☐	☐
This locality is highly polluted with plastics	☐	☐	☐	☐
Plastic waste is well managed in the city	☐	☐	☐	☐
The city highly polluted with plastics	☐	☐	☐	☐

20. Consider each of the following, indicate how much you support or oppose them.

	Strongly disagree	*disagree*	*Agree*	*Strongly Agree*
A ban on plastics				
It is important to recycle your plastic waste.				
Would you like to pay extra amount for the reusable alternatives				

Risk Perception

21. Do you think plastic waste is a problem for human health and environment?
    - ☐ Yes ☐ No ☐ Not Sure

22. If yes, what are these problems?
    - ☐ Makes the city dirty ☐ Clogs drains and causes flooding
    - ☐ Pollutes water bodies and the sea ☐ All of the above

☐	Releases chemicals into the environment	☐	None of the above
☐	Severely impacts animals and birds	Other:	________________________
☐	Causes diseases in humans when ingested		

23. How serious a threat do you think plastic pollution poses for each of these

	Not serious	*Slightly serious*	*Serious*	*Very serious*
Freshwater environments	☐	☐	☐	☐
Marine environments	☐	☐	☐	☐
Wildlife (Animals and plants)	☐	☐	☐	☐
Human Health	☐	☐	☐	☐

24. Are you aware chemical compounds used in plastic products leaks from the plastic and has harmful impacts? *

☐ Yes ☐ No

Knowledge on Microplastic

25. Have you ever heard of microplastics?

☐ Yes ☐ No

26. If yes, explain

____

____

27. Do you know that microplastic serve as surfaces for other pollutants and microorganisms to attach including bacteria?

☐ Yes ☐ No

28. Do you know microplastics have been found in human bodies?

☐ Yes ☐ No

THANK YOU

Ethical Clearance

UNIVERSITY OF GHANA
ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES
(ECBAS)

P. O. Box LG 1195, Legon-Accra

Ref. No: ECBAS 066/21-22

22nd September, 2022.

Ms. Millicent Amekugbe
Institute for Environment and Sanitation Studies
University of Ghana
Legon, Accra

Dear Ms Amekugbe,

ECBAS 066/21-22: MICROPLASTICS IN FRESHWATER ECOSYSTEMS: THE CASE OF ODAW RIVER BASIN, GHANA

This is to inform you that the above referenced study has been presented to the Ethics Committee for Basic and Applied Sciences for a full board review and the following actions taken subject to the conditions and explanation provided below:

Expiry Date:	12/09/2023
On Agenda for:	Initial Submission
Date of Submission:	13/07/2022
ECBAS Action:	Approved
Reporting:	Annually

Please accept my congratulations.

Yours sincerely,

APPROVED
22 SEP 2022

Professor Dorcas Osei-Safo
ECBAS Chairperson