MASTER OF SCIENCE IN CIVIL ENGINEERING

Abundance, Characteristics and Ecological Risks of Microplastics in River Sediments around Dhaka City

by

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Gazipur, Bangladesh

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Abundance, Characteristics and Ecological Risks of Microplastics in River Sediments around Dhaka City

A Thesis

by

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It is hereby declared that this thesis/project report or any part of it has not been submitted elsewhere for the award of any Degree or Diploma.

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Dedication

I would like to dedicate this thesis to my parents and all my teachers who brought me up to this moment.

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ABSTRACT

Microplastics (MPs), the small particles of plastics with a size less than 5 mm have been identified as an emerging pollutant in recent decades. Microplastics pose a higher risk in the aquatic environment and also a potential threat to human health. The aquatic species ranging from invertebrates to fishes can easily ingest microplastics along with other contaminants considering MPs as food sources due to their diverse characteristics (size, shape, and color), which accumulate in digestive tracts of aquatic species. Finally, MPs enter into the human body through gastrointestinal ingestion of aquatic species as well as from water consumption and thus create human health risks depending on their toxicity level. Microplastics (MPs) pollution has become an escalating problem in Bangladesh also due to its rapid urbanization, economic growth, and excessive uses of plastics, however data of MPs pollution of fresh water resources is very limited in Bangladesh. This study investigated microplastics pollution in the riverbed sediments in the peripheral rivers of Dhaka city. In total, 28 sediment samples were collected from the selected stations of Buriganga, Turag, and Balu River. A total of about 1 kg of riverbed sediment, 5-10 m away from the shoreline was sampled using an Ekman grab sampler (15×15×15 cm) from top 10 cm of the riverbed at each sampling station. Density separation and wet-peroxidation methods were employed to extract microplastic particles. Attenuated total reflectance-Fourier transform infrared spectroscopy was used to identify the polymers. Scanning electron microscopy (SEM) analysis was performed to examine the surface characteristics of weathered MPs.

MPs in the river sediment were found to vary with sampling locations and the abundance of MPs varies from 46 to 534 items per kilogram (kg) of dry sediment. The mass concentration of MPs varies from 13.56 mg/kg to 430.65 mg/kg with an overall average value of 106.52 ± 73.17 mg/kg. The results indicated a medium-level abundance of microplastics in the riverbed sediment in comparison to other studies in the freshwater sediments around the world. The observed MPs particles were shorted into three shapes: films, fragments, and fibers. Films (53.89%) were the most abundant shapes followed by fragments (37.57%), and fiber (8.54%).. The white (18.77%) MPs were major abundance followed by transparent (14.90%), yellow (14.37%), blue (14.37%), red (12.03%), green (11.27%), black (8.40%) and grey (5.87%). Larger quantities of the plastics are generally used in Bangladesh for shopping bags, package products and textile materials, which are white or transparent in color. MPs are categorized into small microplastics (<1 mm) and large microplastics (1-5 mm). The results of this investigation found that on an average, the riverbed sediments contain large sized MPs (67%) much higher than small sized MPs (33%). The most abundant polymers were polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET).

The pollution load index (PLI) values more than 1 were observed indicating that all sampling sites were polluted with microplastics. An assessment of ecological risks, using the abundance, polymer types, and toxicity of MPs in the sediment samples suggested a medium to very high-level ecological risks of microplastics pollution of the rivers. The average ecological risk index (ERI) value suggested that both BR and TR have high ecological risk and BaR has medium ecological risk. In some sampling locations of both BR and TR, ERI value more than 1200 was observed, indicating very high ecological risk to those sampling locations. Higher abundance of MPs and presence of highly hazardous polymers such as polyurethane, acrylonitrile butadiene styrene, polyvinyl chloride, epoxy resin, and polyphenylene sulfide were caused the higher ecological risks. SEM images revealed that the PE, PP, and PET polymers with the carbonyl group had linear fractures, cracks, pits, grooves, granules, and flakes and along with some crystalline formation. However, the same types of particles without carbonyl group had experienced relatively stable surfaces but still contained rough and irregular textures. This textural analysis suggested that MPs particles in riverine sediment were weathering by various processes, producing smaller MPs, which are caused more potential ecological hazards in these river ecosystems.

This study indicated that the river ecosystem of the peripheral rivers of Dhaka city is polluted by MPs from the anthropogenic sources both point and non-point in nature. MPs pollution of freshwater bodies is a new dimension of the widespread pollution because of increased use of plastic products, reckless and uncontrolled disposal of municipal solid wastes including plastic wastes, disposal of untreated industrial wastewater including plastic industries and excessive urbanization. Finally, this investigation provided a baseline information on microplastics pollution in the riverine freshwater ecosystem for more in-depth study on risk assessment and developing strategies for controlling microplastics pollution in the country.

LIST OF ABBREVIATIONS

ABS	Acrylonitrile–Butadiene–Styrene
ATR	Attenuated Total Reflection
BaR	Balu River
BIWTA	Bangladesh Inland Water Transport Authority
BoPET	Biaxially Oriented Polyethylene Terephthalate
BR	Buriganga River
BR	Butadiene Rubber
DEM	Digital Elevation Model
EDX	Energy Dispersive X-Ray
EP	Epoxy Resin
ERI	Ecological Risk Index
FTIR	Fourier Transform Infrared Spectroscopy
LDPE	Low-Density Polyethylene
MP	Microplastic
MSDF	Marine Strategy Framework Directive
NOAA	National Oceanic and Atmospheric Administration
PES	Polyester
PET	Polyethylene Terephthalate
PHI	Polymeric Hazard Index
PLI	Pollution Load Index
PP	Polypropylene
PPS	Polyphenylene Sulfide
PS	Polystyrene
PUR	Polyurethane
PVA	Polyvinyl Alcohol
PVC	Polyvinyl Chloride
SBR	Styrene-Butadiene Rubber
SEM	Scanning Electron Microscopy
STP	Sewage Treatment Plant
TR	Turag River
USGS	United States Geological Survey
UV	Ultraviolet
WPO	Wet Peroxide Oxidation
WWTP	Wastewater Treatment Plant

CHAPTER 1 INTRODUCTION

1.1 Background

Microplastics (MPs), the small particles of plastics with a size less than 5 mm have been identified as an emerging pollutant in recent decades (Machado et al., 2018). Microplastics spread-out all over the world, found in air, water and sediment and are causing threats for biotic and abiotic systems (Prinz and Korez, 2020). Microplastics themselves, adsorb pollutants including heavy metals and desorb chemical additives, act as a vector of contaminants to organisms following ingestion, create toxicity on global health and environment (Bouwmeester et al., 2015; Carbery et al., 2018; Liu et al., 2021). Microplastics pollution is considered as a potential threat for the ecosystem and challenges to achieve UN SDGs (Walker, 2021).

Microplastics pose a higher risk in the aquatic environment and also a potential threat to human health (Derraik, 2002; Koelmans et al., 2017). The aquatic species ranging from invertebrates to fishes can easily ingest microplastics along with other contaminants considering MPs as food sources due to their diverse characteristics (size, shape, and color), which accumulate in digestive tracts of aquatic species (Carbery et al., 2018; Dawson et al., 2018; Wang et al., 2019). Finally, MPs enter into the human body through gastrointestinal ingestion of aquatic species as well as from water consumption and thus create human health risks depending on their toxicity level (Nadiruzzaman et al., 2022; Yuan et al., 2022). The extent of the negative impacts on humans can be so immense that it can lead to immune system disruption, oxidative stress, neurotoxicity and cytotoxicity (Bhuyan et al., 2022). Therefore, several researchers incorporated risk assessment in their study on MP pollution and more study in diverse environments is also required to understand the comprehensive ecological risk (Kabir et al., 2021, 2022; Peng et al., 2018).

Microplastics in marine environments has given much attentions in the recent year due to its importance on planetary health (Anik et al., 2021; Yuan et al., 2022). In total, 14 million tons of microplastics accumulated in world's oceans and additionally 1.15 to 2.41 million tons of (micro and macro) plastics are entering into oceans annually from the riverine system (Isobe et al., 2021; Lebreton et al., 2017; Napper et al., 2021). However, microplastics in the riverine environment have gained less attention as compared to the marine system (Blettler et al., 2017, 2019). Several researchers investigated the occurrence, types, and characteristics of MPs in the riverine environment in recent times to reduce the current knowledge gaps (Gerolin et al., 2020; Yuan et al., 2022). However, these investigations are mostly limited to few developed countries and the existing literature regarding MPs in the freshwater riverine system remains insufficient in developing countries like Bangladesh (Blettler et al., 2018, 2019).

As a developing country, the uses of plastic items have been increased significantly in Bangladesh with a consumption of 977,000 tons in the year of 2020 (World Bank, 2021). The country's annual per capita plastic consumption in urban areas tripled to 9.0 kg in 2020 from 3.0 kg in 2005 (World Bank, 2021). The capital of Bangladesh, Dhaka's the annual per capita consumption of plastics is 22.25 kg, which is significantly higher than the national average. Lack of individual institutions for idiosyncratic plastics waste management and challenges in implementing environmental policy leads to this excessive plastics generation. Dhaka city is surrounded by three rivers, namely Buriganga river in the south-west, Balu river in the east and Turag river in west-north-east. Dhaka city is the inhabitant of more than 20 million producing about 646 tons of plastic waste daily and most of those are dumped with municipal solid waste to the open landfill sites as well as open areas, waterbodies and rivers due to inadequate collection, disposal and management facilities (Tembon et al., 2021). These plastics convert into microplastics by various environmental processes such as photodegradation, biodegradation, weathering, etc. and entered into the surrounding waterbodies and peripheral rivers of Dhaka city (Wu et al., 2020). In addition, more than 7000 industries including tanneries, plastic molding and recycling, chemical are located in and around the banks of the peripheral rivers. The wastewater from the industries, urban runoff and the domestic wastewater from Dhaka City are mostly discharged directly into the adjacent rivers along with improper waste management cause the massive pollution of the peripheral rivers specially during the dry period (January -April) and also be the major sources of microplastics pollution (Islam et al., 2015). These microplastics pollution in river water create toxicity to aquatic species and impact socioeconomically due to its uses for water supply, navigation, recreation, irrigation and industrial purposes (Chowdhury et al., 2021; Khalid et al., 2021; Wang et al., 2019). Therefore, it becomes urgent to study the MPs pollution status of the peripheral rivers of Dhaka city. The occurrence and characteristics of MPs in sediment, water and aquatic species from the Buriganga river have been studies by Islam et al., 2022 and Haque et al. 2022. However, there is no comprehensive study on MPs pollution and associated ecological risks in other peripheral riverbed sediment of Dhaka city.

The aims of this study were to investigate the abundance and characteristics of microplastics in the riverbed sediment of the surrounding rivers of Dhaka city, identify the probable land use patterns and understand their influence on MPs pollution, and assess the ecological risk of MP through multiple indices. This is the first comprehensive study of the peripheral urban rivers' sediment, which assessed the ecological risk due to MPs pollution from Dhaka city. This knowledge regarding pollution scenarios, sources, characteristics and ecological risk of MPs in this river basin will be useful as baseline and to develop the to control measures for microplastics pollution and risk reduction of this valuable water resources.

1.2 Objectives

The objectives of this study are as follows:

i. To investigate the abundance and characteristics of microplastic in riverbed sediment around Dhaka city (Buriganga, Turag and Balu rivers).
ii. To assess ecological risks of microplastics in riverbed sediment of these rivers around Dhaka city.

1.3 Scope of the Study

The scope of this study is to collect riverbed sediment samples from the peripheral river system of Dhaka city considering land use sources. Microplastic particles were extracted through density separation and wet-peroxidation methods in the laboratory. Microscopic examinations were conducted to identify the characteristics of MPs. Attenuated total reflectance-Fourier transform infrared spectroscopy was used to identify the polymers. Scanning electron microscopy (SEM) analysis was performed to examine the surface characteristics of weathered MPs.

1.4 Organization of the Thesis

The thesis has been presented in five chapters.

Chapter One presents the background of the study, objective, and outline of methodology in brief.

Chapter Two presents a review of the possible sources of microplastics pollution in the aquatic ecosystem, its impact on the overall environment and the means to mitigate the adverse effects. This chapter describes related works which have been performed previously.

Chapter Three presents the methodology followed in this research. It includes details of the sampling and analysis of microplastics in sediment samples, and it describes in detail the laboratory experiments carried out for the quantification and characterization of microplastics. Assessment procedure of ecological risk indices and weathering effect of MPs is also presented.

Chapter Four present abundances and mass concentration of microplastics, and the results of the laboratory experiments for the characterization (shape, size, color and polymer types) of Microplastic in the sediment of rivers around the periphery of Dhaka city. It also presents an assessment of the pollution load, polymeric hazard and ecological risk indices of microplastics including oxidation and weathering of MP particles in the sediment samples around Dhaka City.

Finally, **Chapter Five** summarizes the major conclusions from the present study. It also presents limitations of this study and recommendations for future study.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Plastics can be defined as polymer-based materials manufactured from by-products of fossil fuels and usually processed with a variety of chemical additives (Fan et al., 2019; Gong and Xie, 2020). Due to light-weight, low cost, durability, high persistency, and sound insulation property, the application of plastics has increased exponentially in the last few decades (Gong and Xie, 2020; Tang et al., 2020). More than 8 billion tons of plastics have been produced since their invention, and approximately 55% of them were fabricated in the last two decennaries (Khalid et al., 2021). From 2010 to 2018, in just eight years, global production of plastics has been estimated to rise by 80 million tons (Lusher et al., 2017; Zhang et al., 2020). Even in 2020, the production of single use plastic bags alone was around 0.84 million tons (Foschi and Bonoli, 2019). Plastics with a size range between 100 nm to 5mm refer to microplastics, which can be both directly manufactured at this size range or deteriorated from larger plastics by environmental processes (Stock et al., 2019).

Microplastics are omnipresent throughout the world and reported to be detected even at sea around Antarctica, where population density is almost zero (Barnes et al., 2010). Microplastics cause more danger to the environment than larger plastics (Zhang et al., 2020), and it is estimated that almost 10% of the total plastic litters in the aquatic environment eventually converts into microplastics by various external forces such as UV radiation, heat, water, biota, etc. (Wu et al., 2020).

From tiny-sized resin pellets to extensive packaging material, no matter the size, any product made of plastic have the potential to contribute to the occurrence of microplastics in river sediment. However, the significant sources of microplastics include personal care product (Sun et al., 2020), pellet, blasting agent (Duis and Coors, 2016), fabric (Fontana et al., 2020), packaging material (Foschi and Bonoli, 2019), vehicle tire (Chen et al., 2020), fishing gear, etc. The distribution of microplastics around the globe is not uniform and mainly depends on the nature of the aquatic system, climate, as well as characteristics and sources of microplastics (Redondo-Hasselerharm et al., 2018). Several researchers had investigated the condition of microplastic pollution in river sediment at various locations (Constant et al., 2020; Eo et al., 2019; Jiang et al., 2019; Nel et al., 2018; Peng et al., 2018). Nevertheless, the results of these studies are difficult to compare as they have performed microplastic analysis using different methodologies. Moreover, a wide range of variation is observed in the criteria of microplastics classification depending upon researchers. For example, (Wu et al., 2020) classified microplastics into four shapes such as fiber, foam, film, and fragment but (Liu et al., 2021) separated lines and fibers into two different categories.

2.2 Sources and Pathway of MPs in River Sediment

Identification of the sources of microplastics is important to perceive the pathway and impact of microplastics and to evolve the mitigation strategies (Tang et al., 2020). To develop an understanding of the sources of microplastics, we need to differentiate between primary and secondary microplastics (Waldschläger et al., 2020). Primary microplastics are designed and produced at the size range of microplastics, (<5 mm) which can be used as the raw material of personal care products, cosmetics, and other industrial products (Gong and Xie, 2020; Simon-Sánchez et al., 2019; Yang et al., 2021). On the other hand, secondary microplastics are the result of physical, chemical, and biological degradation and fragmentation of larger plastics when exposed to the environment (Fred-Ahmadu et al., 2020; Waldschläger et al., 2020).

2.2.1 Sources of primary microplastics

Microplastics (microbeads, sodium tetraborate decahydrate, etc.) with a diameter of less than 5mm are used as polishing agent in personal care products such as cosmetics, hand sanitizer, facewash to remove dead cells from the surface of the skin (Duis and Coors, 2016). An investigation on peeling, toothpaste, body wash, and scrub found that the amount of polyolefin microplastics used in consumer products ranges from 0.45 %(w/w) to 7.48 % (w/w). Another study found that approximately 94500 breads could be exerted from each facial cleansing product (Ngo et al., 2019). Moreover, on average, 2450 particles/g were detected in facewash, and in Slovenia, this count reaches the maximum (3.11×106 particles/g) (Sun et al., 2020). Comparatively, fewer microplastics (2.15 particles/g) were found in body wash (Sun et al., 2020).

Resin pellets used in the production of plastic and other industrial activity is one of the significant sources of primary microplastics (Duis and Coors, 2016; Yang et al., 2021). Though numerous studies were conducted on the occurrence of plastic production pellets in the beach samples (Acosta-Coley and Olivero-Verbel, 2015; Antunes et al., 2013; Turner and Holmes, 2011), investigation in river sediment is still in headway. In Wen-Rui Tang River, pellets were 12.8% of the total microplastics (Wang et al., 2018).

Glitters which can be defined as tiny, smooth, and beautifying material made of biaxially oriented polyethylene terephthalate (BoPET) also comprise the source of microplastics (Yurtsever et. al., 2019). An investigation performed on the wastewater treatment plants in Norway found that glitters contribute 1.7% (in weight) of total microplastics detected in the sample (Lusher et al., 2017).

Blasting agents such as acrylic, polyester (PES) used to remove paint or other contaminants from the metal surface, roughen any surface, or clean mechanical engines are another possible source of primary microplastics (Duis and Coors, 2016; Waldschläger et al., 2020).

2.2.2 Sources of secondary microplastics

Due to high removal efficiency in the sewage treatment plant and proper caution during handling, fewer primary microplastics are usually identified in the river sediment (Duis and Coors, 2016; Gong and Xie, 2020). So, secondary microplastics are the main contributor of microplastics in the river (Yang et al., 2021).

Around 60% of the total manufactured fibers in the world are synthetic fibers such as polyester, acrylic, cotton, nylon (Dalla Fontana et al., 2020). These synthetic fibers can be detached during the laundering process of fabric and disposed into the environment as secondary microplastics (Waldschläger et al., 2020). In Ciwalengke River, around 93% of the detected microplastics in the sediment were fiber, and the result from Raman spectra analysis indicates that these microfibers were produced from shredded fabrics (Alam et al., 2019). Depending on the clothing and washing process, one to ten hundred microplastics was extracted from washing effluent in the laboratory with a filter of 5 mm width and 4.7 mm dia (Falco et. al., 2017). Furthermore, it is estimated that approximately 6000000 microplastics per 5 kg wash load can be released in the effluent of the textile industry (Yang et al., 2021). Even in the domestic wash, the amount of released fiber can be around 700000 per 6 kg wash (Napper et. al., 2016). Another study investigated that the rate of microplastics release from finished clothing lies between 175 to 560 microfibers per gram (30000-465000 microfibers per m^2) fabric (Belzagui et al., 2019). The detachment rate of microfibers is comparatively higher in woven polyester, but this rate can be decreased by more than 35% by using softener instead of regular detergent during the washing process (Falco et. al., 2017).

Plastic is a cheap, lightweight material that gives good protection against moisture (Andrady et. al., 2011). Due to these properties, plastic is widely used as packaging material for food, dish, cutlery, and other products (Foschi et. al., 2019). The global production of plastic packages is 75-80 million tons each year (Andrady et. al., 2011). Therefore, in Europe and China, packaging industries are considered the most substantial source of plastic pollution (Tang et al., 2020). Most of these packages are disposable one-time use products, discarded into the environment, and end up as secondary microplastics. Moreover, there is evidence of generating microplastics during the scissoring or tearing of these packages.

Plastics such as low-density polyethylene (LDPE) are commonly used in the production of rope, floating drilling rig, and other fishing gears used in aquaculture (Tang et al., 2020). Due to abrasion or some other reason, microplastics can shred away from these tools during fishing activities (Chen et al., 2020). So, aquaculture and fisheries are potential sources of secondary microplastics (Andrady et. al., 2011). A study on microplastic pollution due to fishing activities detected 571$\pm$409 particles/kg sediment in the adjacent suburban rivers of the Beibu Gulf, and this count was even more (735$\pm$405 particles/kg sediment) in the adjacent urban river. Another investigation was conducted in aquaculture water of Pearl River Estuary where 10.3-60.5 particles/L and 33.0-87.5 particles/L of water sample were extracted in two experimental stations (Ma et al., 2020), which can end up in the river sediment or ocean.

Polymers such as butadiene rubber (BR) and styrene-butadiene rubber (SBR) are one of the widely used components of vehicle tires (Waldschläger et al., 2020). While driving, these polymers can wear out due to friction between the road surface and tire (Kole and Löhr, 2017). Thus, wear and tear from vehicle tires are considered as one of the significant sources of secondary microplastics (Ngo et al., 2019). In Japan, approximately 239,762 tons of wear and tear is released from tires each year (Kole and Löhr, 2017), and the emission of microplastics from wear and tear is around 240 kilotons per year (Ngo et al., 2019). Moreover, microplastics from vehicle tires contribute around 3-7% of the total dust, spores, and pollen($PM_{2.5}$ particles) in the air (Kole and Löhr, 2017).

Besides, except the sources mentioned above, construction materials such as pipes, insulating materials, etc., sporting goods such as artificial turfs, goal nets, etc., can also be the potential contributor of secondary microplastics (Waldschläger et al., 2020). However, research on their contribution to microplastic pollution is still in the developing phase.

2.2.3 Degradation of plastics under aquatic environment

Degradation mainly refers to the decomposition of plastics by chemical alteration (Waldschläger et al., 2020). In other words, degradation incorporates either oxidation or hydrolysis process through which plastic losses its mechanical integrity and molecular weight (Andrady, 2011; Chamas et al., 2020). It can be induced by various degradation forces such as radiation (photodegradation), heat (thermal degradation), living organism (biological) and water (hydrolytic degradation), etc. (Cassidy and Aminabhavi, 1981). The rate of disintegration of any degradation process is comparatively slower than photodegradation (Andrady, 2011). Thus, in this literature review, only the process of light-induced degradation, namely photodegradation or photo-oxidation, along with biodegradation will be discussed.

2.2.3.1 Photodegradation

The mechanism of photodegradation initiates with the absorption of UV-B radiation of sunlight by plastics (Andrady, 2011). UV-B radiation that reaches earth (wavelength 2900-4000 Å) has energy ranges from 72-97 Kcal/mole, which is adequate to disintegrate any chemical bond, with few exceptions such as N-H, O-H, C-H, etc. (Cassidy and Aminabhavi, 1981). The application of sunlight on polymers stimulates a chemical chain reaction in which a hydrogen atom (H•) is removed from an exciting polymer molecule (RH) and produces a free polymer radical (R•) (Chamas et al., 2020).

$$\text{Initiation: RH} \xrightarrow{UV-B} RH^*$$

$$\text{R}H^* \rightarrow \text{R• + H•}$$

This polymer radical (R•) combines with oxygen (O_2) to form a peroxy radical (ROO•) which then reacts with adjacent polymer molecule (RH), extracts hydrogen atom (H•) from it and produces a new polymer radical (R•) as well as a hydroperoxide (ROOH) group (Rånby, 1993).

$$\text{Propagation: R•} + O_2 \rightarrow \text{ROO•}$$

$$\text{ROO• + RH} \rightarrow ROOH + \text{R•}$$

Hydroperoxide (ROOH) is susceptible to change in the presence of light(Yousif and Haddad, 2013). It breaks down into alkoxy (RO•) and hydroxyl radical (OH•), each of which produces another polymer radical (R•), and thus photodegradation continues through chain propagation (Chamas et al., 2020).

$$\text{Propagation: ROOH} \rightarrow \text{RO•} + \text{OH•}$$

$$2\text{ROOH} \rightarrow \text{RO•} + \text{ROO•} + H_2O$$

$$\text{RO•} + \text{RH} \rightarrow \text{ROH} + \text{R•}$$

Chain propagation terminates when radicals combine and form non-radical stable products (Rånby, 1993; Yousif and Haddad, 2013).

$$\text{Termination: ROO•} + \text{ROO•} \rightarrow \text{ROOR} + O_2$$

$$\text{R•} + \text{R•} \rightarrow \text{R-R}$$

$$\text{ROO•} + \text{R•} \rightarrow \text{ROOR}$$

β-scission of alkoxy radical (RO•) results in the formation of oxidized groups such as carboxyl, carbonyl, etc., which may promote further chain scission by photolysis of Carbonyl functional groups (C=O) (Cassidy and Aminabhavi, 1981; Yousif and Haddad, 2013). Carbonyl photolysis advances either through Norrish Type I or Norrish Type II reaction (Rånby, 1993). Norrish Type I reaction refers to photochemically induced homolysis of carbonyl group into two free radical intermediates, whereas Norrish Type II reaction refers to light-induced intramolecular extraction of a γ-hydrogen to produce alkene and enol or enable cyclization of carbonyl compounds to cyclobutanols (Chamas et al., 2020; Scheffer et al., 1986).

As the key role of radiation is to introduce chain initiation reaction, further degradation can proceed at moderate temperature without any exposure to sunlight (Andrady, 2011). So, photodegradation and thermal degradation are indistinguishable under usual conditions. But in the absence of UV radiation, minimum of 100 °C temperature will require to start the thermal degradation of Polyethylene (PE) (Chamas et al., 2020). However, studies have found that polyester (PET) and polyamide (PA) are comparatively less persistent and easily degradable than polyacrylonitrile (PAN) under exposure to sunlight (Sait et al., 2021). An overview of the photodegradation process of MPs is shown in Figure 2.1

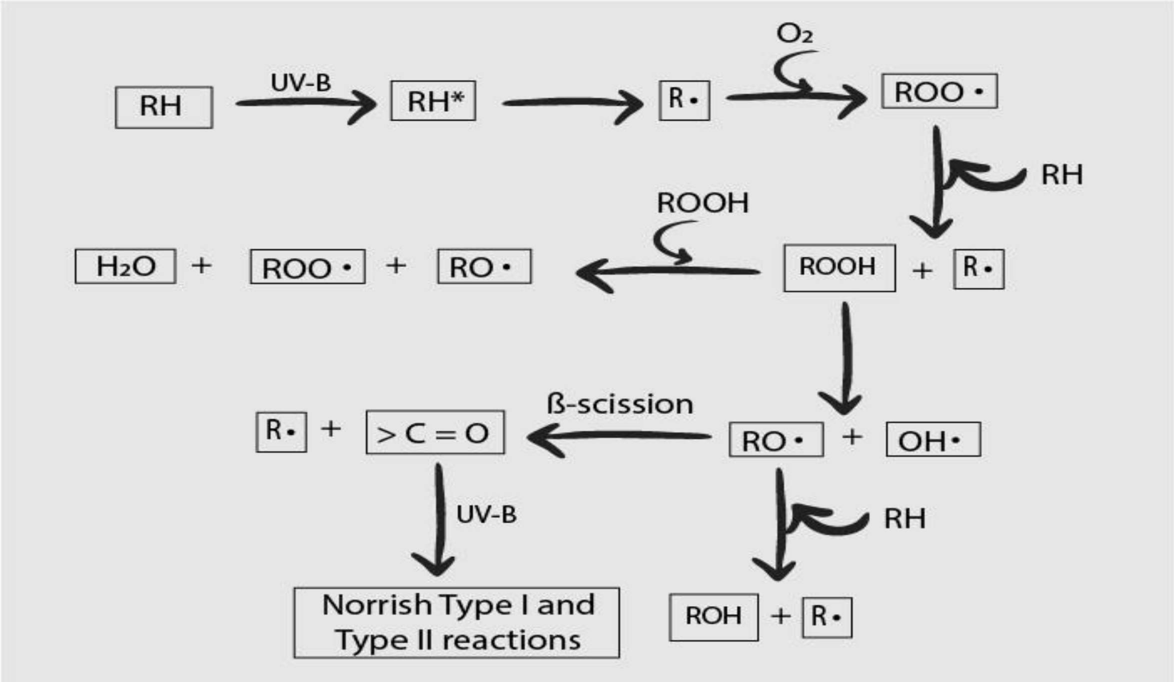


Figure 2.1: Overview of the photodegradation process of MPs

2.2.3.2 Biodegradation

After extensive photodegradation and fragmentation by wave, wind, and rain, microplastic particles will undergo biodegradation (Cassidy and Aminabhavi, 1981). Biodegradation is a slow process through which polymers convert into biomass and eventually disappear (Andrady, 2011). This process is affected by several factors that include polymer characteristics such as molecular weight, size, shape, surface area, etc., type of organism and nature of their enzyme, characteristics of abiotic exposure such as pH, temperature, moisture, and nature of pre-treatment (Ahmed et. al., 2018). The mechanism initiates with the attachment of exoenzymes secreted by microbes to polymer fragments (Ahmed, 2018). The role of exoenzymes is to cleave the polymer chains and convert them into monomers, dimers, or oligomers. Monomers, dimers, or oligomers are lightweight molecules with shorter chains and can easily penetrate bacterial cytoplasm. The assimilated molecules are utilized by the microorganisms to produce energy, new cells, and other metabolic products (Cassidy and Aminabhavi, 1981) and converted into water, carbon dioxide (aerobic condition), or methane (anaerobic condition) as the end product (Ahmed et. al., 2018). An overview of the degradation process of plastic is shown in Figure 2.2.

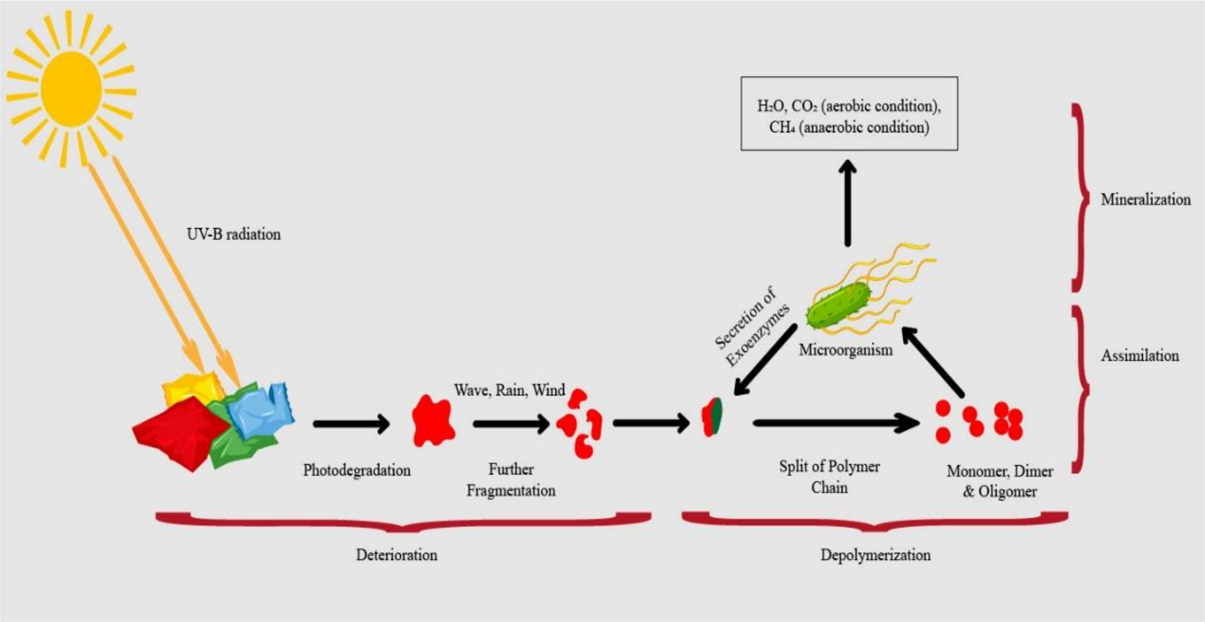


Figure 2.2: Overview of the degradation process of plastics.

2.2.4 Pathways of MPs to the river sediment

Microplastics do not remain confined to one environmental element; instead, they migrate from one to another (Gong and Xie, 2020). Pathways of microplastics to the river sediment can be described from the following perspective: a) direct discharge of microplastics by land-based activities, b) release of microplastics with treated and untreated wastewater, and c) release of microplastics by water-based activities (Tang et al., 2020)

Land is considered the most significant contributor of microplastics in the aquatic environment (Gong and Xie, 2020; Yang et al., 2021). Some portion of microplastics from waste yards, agricultural fields, roads, and other sources directly move into the river with surface runoff; some portion travels into the subsurface first then reaches the river with subsurface runoff (Gong and Xie, 2020; Yang et al., 2021) and rest enters into the sewage system (Waldschläger et al., 2020). Lack of wastewater treatment facility in municipality results in the discharge of microplastics into the river with sewage wastes. For instance, due to the disposal of untreated sewage wastes at numerous points, a moderate amount of microplastic particles (96 pieces/kg of dry sample) was detected in the shoreline sediment of the Netravathi river (Amrutha and Warrier, 2020). Furthermore, the sewer system with a proper treatment facility can also be a substantial source of microplastic despite its high removal efficiency (Yurtsever, 2019). Similarly, microplastics can also migrate into the river with industrial wastewater. A study found that a single secondary wastewater treatment plan can introduce 23 billion microplastics into the environment annually (Murphy et al., 2016). Sludge from the wastewater treatment plant can be used as landfill and fertilizer in the agricultural field from which microplastics can enter the aquatic environment by the action of wind and rain (Waldschläger et al., 2020). In addition, some microplastics are directly discharged into the river by water-based activities such as navigation, fisheries, and port activities (Tang et al., 2020). In a river with low flow velocity, microplastics with a density greater than water readily settle down and accumulate in the benthic sediment (Nizzetto et al., 2016). In contrast, in a river with high flow velocity, particles will move with the flow into a low-velocity zone and then settle down (Nizzetto et al., 2016). Particles with a density lower than water usually float and end up into the ocean but can be retained in the river sediment by biofouling and agglomeration (Waldschläger et al., 2020). Biofouling refers to the colonization of microorganisms on the surface of microplastics (Andrady, 2011). The process starts with the formation of a biofilm with algae, spores, and other dissolved matter on the surface of microplastics which enables ease attachment of colonizing microbes (Coyle et al., 2020). The density of particles tends to increase with biofouling, allowing the particles to sink when it transcends the density of water (Coyle et al., 2020). Usually, microplastics smaller than 0.2 mm do not end up in the river sediment regardless of density (Nizzetto et al., 2016). Pathways of MPs to the river sediment is shown in Figure 2.3.

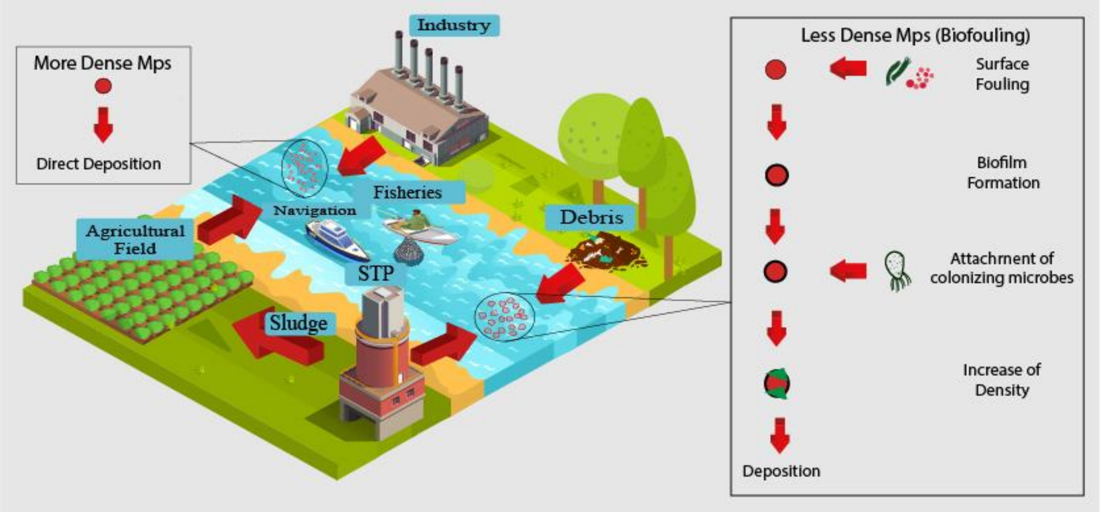


Figure 2.3: Pathways of MPs to the river sediment.

2.3 Microplastics Analysis Methodology

Although several researchers have conducted research on microplastic since two decennaries, standardized methodologies for microplastic analysis have yet to develop (Li et al., 2018; Yang et al., 2021). This paper has reviewed previous studies to overview sample collection, preparation, and analysis methods of microplastic in river sediment and summarized them in Table B.1 and Table B.2. Overall microplastic analysis methodology can be divided into four steps: Sample collection, sample preparation, sample extraction and purification and identification and quantification. Different steps in microplastics analysis methodology are shown in Figure 2.4.

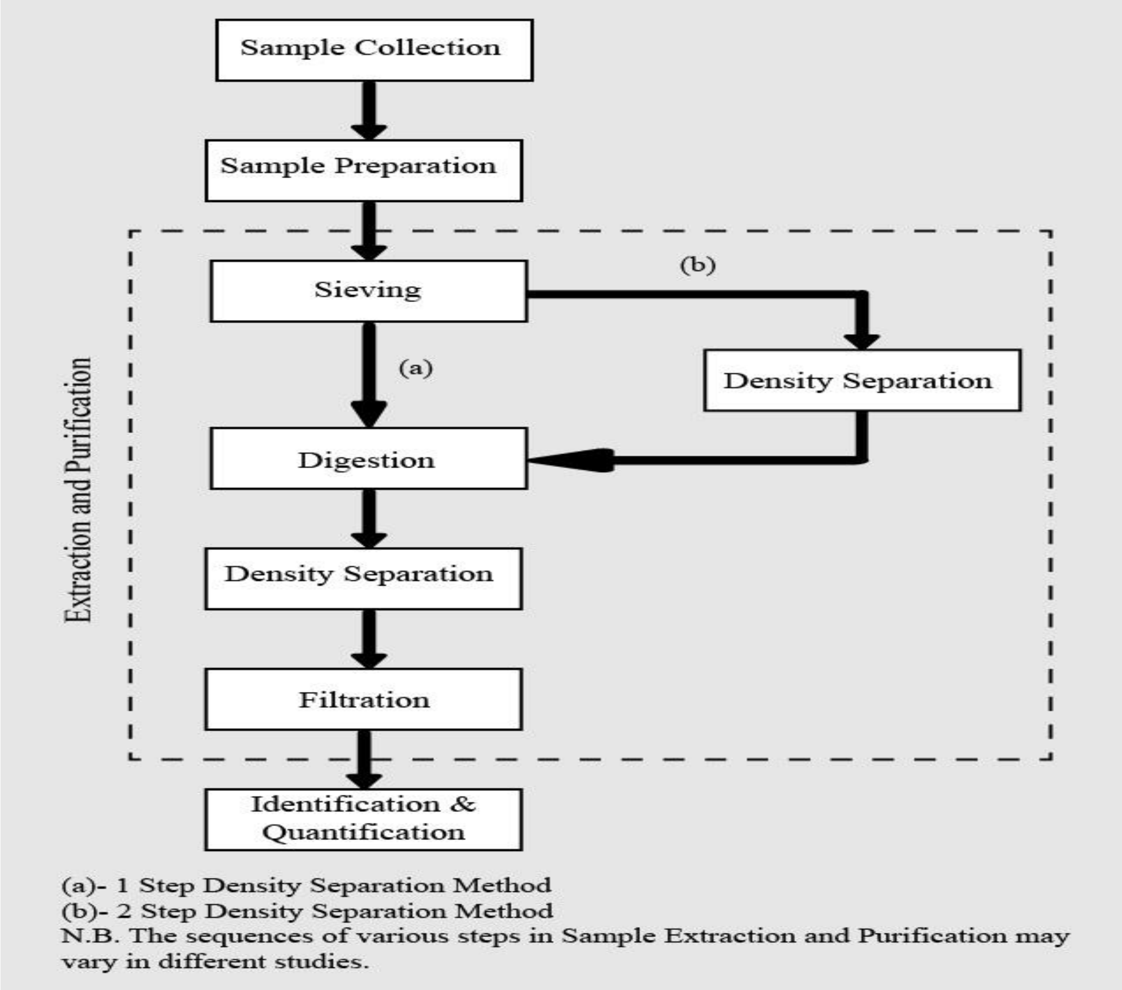


Figure 2.4: Different steps in microplastics analysis methodology.

2.3.1 Sample Collection

Though sample collection strategy mostly depends on the objectives of the study, it is expected to collect the maximum possible number of samples in order to gain an accurate and deep understanding of the distribution and quantity of microplastic particles in sediment (Stock et al., 2019).

The methods of microplastic sampling in freshwater sediment can be categorized into three (Hidalgo-Ruz et al., 2012a):

a) **Selective Sampling**: In this method, microplastics are directly picked from the field samples via visual inspection (Gong and Xie, 2020). This method was not adopted in any of our reviewed studies. However, it can be suitable for samples that contain a huge amount of large microplastic particles (1-5 mm diameter) (Yang et al., 2021).

b) **Volume-reduced Sampling:** In this method, only the portion of the sample necessary for further processing is preserved to decrease the volume of the bulk sample (Silva et al., 2018). The sample of interest can be retained by filtering or sieving(Gong and Xie, 2020).

c) **Bulk Sampling:** Entire sample is collected without reducing its size (Silva et al., 2018).

Samples can be collected from both shoreline and riverbed. Shoreline sample offers relatively larger area for sampling in a quick and cost-efficient way, but riverbed sample offers comparatively less disturbed sample as the riverbed is less influenced by natural and anthropogenic activity (Adomat and Grischek, 2020). Shoreline or riverbed, which should be sampled, largely depends on research perspective, availability of collection tool, and expert opinion (Adomat and Grischek, 2020). In most of our reviewed studies, van veen grab sampler or stainless-steel shovel was used as sample collection tools. Besides, steel trowel, Peterson grab sampler, grab bucket (B-10104), box corer, grasp bucket, stain-less steel spatula, stain-less steel spoon, cole-parmer sediment sampler, ponar stain-less steel grab sampler, perspex tubes, quadrat was also used in different studies. To be more specific, stain-less steel shovel, spoon, and spatula were used to collect bulk samples from shoreline or riverbank and to collect samples from the middle or center of the river Van Veen grab sampler or Peterson grab sampler were used. Box corer offers less variability in penetration depth during sampling of sediment from the bottom of freshwaters and oceans. Howeber, Van veen, Petersen, and Ponar grab sampler do not require any winch or crane to operate, unlike box corer sampler (Brander et al., 2020).

Definition of sampling depth is important for achieving higher accuracy in determining microplastic concentration in sediment samples (Prata et al., 2019). Moreover, Average microplastic concentration can be higher in the top 1-5 cm sample than the top 10 cm sample (Besley et al., 2017). In most of our reviewed studies, sampling depths were defined as the top

5 cm or top 10 cm of the sediment. Besides, some of the studies had collected samples from the top 2 cm,15 cm, and even 20 cm of the sediment.

The laboratory method for microplastics analysis developed by NOAA recommends gravimetric analysis of microplastic in sediment samples. However, as the weight of sediment sample is influenced by water content and sediment type, it is suggested by MSDF to use volume as sampling unit instead of weight (European Commission. Joint Research Centre. Institute for Environment and Sustainability. and MSFD Technical Subgroup on Marine Litter., 2013). But most of the studies used weight as the sampling unit, which varies from 200 g to 2000 g and few studies used area as the sampling unit, which ranges from 0.01 m^2 to 0.09 m^2.

In order to reduce contamination, the use of plastic equipment should be eschewed during sample collection (Adomat and Grischek, 2020). Hence, Samples are usually stored in aluminum or glass containers. In some cases, samples are stored in polyethylene bags but are folded in aluminum foil first.

2.3.2 Sample Preparation

To avoid variability in moisture content of sediment samples, microplastic concentration is suggested to be expressed as dry weight (Cauwenberghe et al., 2015). So, residual moisture should be driven off to a constant weight preceding analysis (Yang et al., 2021). Samples can be dried in both oven and air. Interior of oven prevents airborne pollution of sediment sample during the oven drying process (Adomat and Grischek, 2020), but the higher operating temperatures may crack and distort the shape of microplastic (Zobkov and Esiukova, 2017). Nevertheless, in some studies, samples are dried at high temperatures by omitting common polymers that are vulnerable to heat distortion (Blair et al. , 2019) or eliminating heat distortion effects from consideration (Amrutha and Warrier, 2020; Rodrigues, 2018). In most of our reviewed studies, drying temperature varies from 40° C to 90°C, and in few studies, samples were heated at high temperature of greater than 70°C. In one study, samples were dried in air at room temperature, which may prolong drying time, contaminated the sample with airborne pollutants, and may have residual moisture content even after completion of the drying process (Adomat and Grischek, 2020).

2.3.3 Extraction and Purification

2.3.3.1 Sieving

Sieving is a primary extraction process where sediment samples are passed through sieves of various openings to trap microplastic particles and to separate impurities like clay and silt-sized particles from sediment samples (Gong and Xie, 2020). It can be classified as dry sieving and wet sieving. Due to electrostatic charges in the surface, fine particles agglomerate together and may retain on sieve during dry sieving. So, dry sieving is not adequate for particles finer than 40 µm. Wet sieving can be efficient for particles up to 20µm but may discard low-density microplastic particles unconsciously (Adomat and Grischek, 2020). Sieving step can be omitted during microplastic analysis in order to include fine-sized microplastic fractions in the study (Wang et al., 2018) or if there is no visible debris in the sample (Di and Wang, 2018).

2.3.3.2 Digestion

Sample purification or digestion is a pretreatment process for removing organic matter from sediment samples to avoid disruption of accurate extraction and categorization of microplastics (Adomat and Grischek, 2020; Gong and Xie, 2020). Acid, alkaline, enzyme, 10-30% H_2O_2solutions, Fenton's reagent can be used to treat biological samples.

35%H_2O_2 solution is proved to be efficient by some studies to remove organic matter from sediment samples (Nuelle et al., 2014). Moreover, standardization of digestion method is moderately being developed by using H_2O_2 solution at controlled temperature in a specific digestion period (Y. Zhang et al., 2020). H_2O_2 digestion may result in discoloration and size reduction of polymer particles > 1 mm in size (Nuelle et al., 2014). On the contrary, (Hurley et al., 2018) have found no visible changes for most of the polymer types during H_2O_2oxidation.

A mixture of H_2O_2 and Ferrous Sulfate ($FeSO_4.7H_2O$) catalyst, namely Fenton's reagent, can be an alternative to H_2O_2 digestion (Adomat and Grischek, 2020). The reaction rate of Fenton's reagent is more rapid and can more efficiently degrade organic matter that is laborious to remove in traditional H_2O_2digestion (Hurle y et al., 2018). But pH requirement (3.0-5.0) for the dissolution of ferrous sulfate and effective digestion of organic matter may degrade some microplastics to a certain degree (Neyens and Baeyens, 2003).

Some studies use acid or alkali for the oxidation of sediment samples. But variability in chemical resistance of different types of microplastic may limit the application of strong acid and alkali digestion (Gong and Xie, 2020). For example, the use of sulfuric acid, nitric acid, or sodium hydroxide may cause the degradation and melting of microplastic particles (Hurley et al., 2018). On the other hand, low concentration of acid and alkali exhibit low removal efficiency; excess organic compounds may remain in the sediment samples at the end of digestion (Nuelle et al., 2014).

Enzyme digestion is another alternative for the extraction of microplastic from organic-rich samples. Like Fenton's reagent digestion, enzyme digestion may require certain pH conditions, which can deteriorate some sensitive microplastics (Adomat and Grischek, 2020). Nevertheless, Proteinase-K enzyme digestion can achieve more than 97% removal efficiency without affecting the morphology of microplastics (Cole et al., 2015). The applicability of enzyme digestion is limited to small-volume samples only due to the high expense of enzymes (Hurley et al., 2018). Although enzyme can be used in combination with $\mathrm{H_2O_2}$ to reduce expense of the research, it takes several days to digest organic matters efficiently (Löder et al., 2017). Thus, none of our reviewed studies used this technique for the oxidation of sediment samples.

2.3.3.3 Density Separation

As the collected sediment samples are mixed with impurities like inorganic clay, separation or extraction of microplastics must be performed during analysis (Gong and Xie, 2020). All the studies used density separation for microplastic extraction. Using the dissimilarity of density between microplastic and non-microplastic particles is the principle of the density separation method (Gong and Xie, 2020). In this method, saturated or highly dense salt is thoroughly mixed with the sediment sample, which allows the low-density particles like microplastics to float and high-density particles like impurities to settle down (Li et al., 2018). Consequently, microplastics are extracted from the supernatant of the solution.

Saturated NaCl solution is a non-lethal, non-abrasive, and economical material, which makes it the most widely used solution for density separation (Yang et al., 2021). The major drawback of this solution is the low extraction efficiency of high-density microplastics like polyethylene (PET) and polyvinyl chloride (PVC) due to its comparatively low density (1.2 $\mathrm{g.cm^{-3}}$)(Amrutha and Warrier, 2020).

Zinc chloride solution ($ZnCl_2$) (density: $1.8 g.cm^{-3}$) eliminate the limitation of NaCl solution and allows floatation of all types of polymer (Tien et al., 2020). A study found that $ZnCl_2$ solution can extract microplastics with a high recovery rate of 95.8% (Coppock et al., 2017). Since $ZnCl_2$is a perilous solution, recycling and reusing of this solution should be ensured to circumvent environmental degradation (Li et al., 2018).

2.3.4 Identification and Quantification

Identification is the most important part of the microplastic analysis and can be performed by visual and/or spectroscopic inspection. The purpose of the visual investigation is to sort out presumed microplastics for further identification based on physical attributes like shape, size, and color (Zhang et al., 2020). Sorting can be done by the naked eye or in assistance with a microscope (Hidalgo-Ruz et al., 2012). Various types of microscopes such as stereoscopic microscope (Jiang et al., 2019; Simon-Sánchez et al., 2019), metallographic microscope (Ding et al., 2019), fluorescence microscope (Wu et al., 2020), light microscope (He et al., 2020), etc. are used during visual inspection. Among them stereoscopic microscope is considered the most used microscope.

2.3.4.1 Visual Inspection

Visual sorting may depend on the examiner’s perspective, quality of microscope, and condition of sediment sample (Li et al., 2018). So, this type of inspection is open to bias and may result in the misidentification of microplastics (Yang et al., 2021). It seems difficult to identify particles smaller than 100 μm in size, and even veteran operators sometimes confound microplastics with organic particles (Eerkes-Medrano et al., 2015; Hanvey et al., 2017). The accuracy of visual inspection decreases with the decrease of particle size (Gong and Xie, 2020), and the rate of misidentification can be as higher as 70% (Hidalgo-Ruz et al., 2012). For instance, (Horton et al., 2017) analyzed 336 visually identified particles under Raman spectroscopy and found only 111 particles (33%) chemically identifiable.

Selection of plastic particles during visual identification should be based on the following criterion: particles must be free from organic impurities, must have consistency in thickness, and homogeneity in color across its length, transparent or white microplastics must be identified with the help of a fluorescence microscope under high magnification to avoid organic particles (Hidalgo-Ruz et al., 2012). Nevertheless, sometimes irregularity in the edge of colored fiber, bleaching, biological contamination, and design of plastics are taken into deliberation (Simon-Sánchez et al., 2019). It is preferable to examine the microplastics on the filter surface without transferring to any other container to avoid loss (Yang et al., 2021), and the investigation should be performed from the top left to the bottom right to avoid duplicate counting (Simon-Sánchez et al., 2019).

Apart from identification purposes, surface characteristics of microplastics and the effect of ultrasonic cleaning on polymers can be investigated by a Scanning electron microscope (SEM) (Wu et al., 2020). Microplastics identified from the spectrometric analysis are wrapped with a thin gold or platinum film and then mapped using SEM. As degraded particles are heterogeneous, visual inspection should be repeated at least thrice to avoid inaccuracy (Wang et al., 2017).

2.3.4.2 Spectrometric analysis

Spectrometric analysis is performed in order to investigate the chemical composition of microplastics (Gong and Xie, 2020). Besides, It can be used to assess visual sorting and correct the particle count determined from visual inspection (Constant et al., 2020). The principle of spectrometric analysis is to detect vibration from agitated samples and compare the produced spectra to the known reference spectra (de Souza Machado et al., 2018; Elert et al., 2017; Mai et al., 2018). Fourier transform infrared (FTIR) and Raman spectroscope is the most widely used spectroscope for the analysis of microplastic (Hidalgo-Ruz et al., 2012).

FTIR can function in three modes- Reflection, transmission, and attenuated total reflectance (Yang et al., 2021). FTIR is widely operated by attenuated total reflection (ATR), in which particles are individually identified and detected by an ATR tip (Lee and Chae, 2021). The well-established database and high signal-to-noise ratio are major attractions of this feature (Yang et al., 2021). Micro-FTIR is developed by attaching an optical microscope with FTIR to analyze smaller particles (Ivleva et al., 2017) which either pose transmission or reflection mode of operation (Li et al., 2018). The prerequisite of transmission mode is the penetration ability of infrared light through the samples, limiting its applicability in dark, opaque and thick samples (Gong and Xie, 2020). Reflection mode allows the analysis of thick, non-transparent particles. But in this feature, particles must be regular in shape; otherwise, uninterpretable spectra will be produced due to the scattering of light (Harrison et al., 2012). Integration of focal plane array (FPA) detector with FTIR is the recent extension of FTIR spectroscopy (Tagg et al., 2015). In this mode, individual particles can be analyzed within a specific grid area using the precision linear mechanism that provides motion in 3 degrees of freedom (Lee and Chae, 2021). FPA detector develops chemical image mapping, which enables the identification of heterogeneous particles (Ivleva et al., 2017). It can detect particles larger than or equal 20 μm and provide information on polymer type, shape and size of each particle separately (Löder et al., 2015; J.-L. Xu et al., 2019). As FPA-FTIR needs to handle huge datasets, the analysis is very time-consuming (Löder et al., 2015). Moreover, samples must be free from organic impurities to avoid hindrance in FPA-FTIR analysis (Chen et al., 2020). The major advantages of FTIR spectrometric analysis are quick and effective identification of microplastic without the influence of fluorescence and the ability to detect the degree of weathering (Gong and Xie, 2020). The major limitation of FTIR spectrometric analysis is its sensitivity towards moisture (Li et al., 2018) . Most of the reviewed studies used FTIR for spectroscopic analysis.

Unlike FTIR spectrometry, wet samples can be analyzed in Raman spectroscopy (RM) (Ivleva et al., 2017). RM offers high spatial resolution so particles less than 20 μm can be easily detected (Gong and Xie, 2020). Moreover, when microscopy is added with RM spectra, it even allows the analysis of submicron particles (<1 μm) (Imhof et al., 2016). In contrast, RM spectrometry is not fit for the samples that are sensitive towards fluorescence action. So, samples need to be free from additives, pigment, cellular, organic, and inorganic impurities (Gong and Xie, 2020; Yang et al., 2021). Another possible drawback of RM spectroscopy is the misidentification of photodegraded particles (Silva et al., 2018). For example, the spectrum of photodegraded PVC illustrates a concurrent depletion of the peak at 693 and 637 cm^{-1} , which is similar to the characteristics of C-Cl (Lenz et al., 2015). Moreover, chemical mapping using RM spectrometry is a comparatively time-consuming process (Ivleva et al., 2017). In comparison with FTIR it can be concluded that FTIR is more efficient to identify polar groups of polymer while RM shows better result of identifying non-polar and symmetric bonds (Silva et al., 2018).

Pyrolysis-GC/MS is another alternative for microplastic analysis where the chemical composition of microplastic is determined by analyzing thermally decomposed products (Nuelle et al., 2014). Since it is a destructive method, it does not determine the amount, shape and size of microplastics (Zhang et al., 2020). Rather it only provides information about the type and mass fraction of chemical components (Dümichen et al., 2015). In addition, it is not possible to distinguish between polymer subtypes, such as whether the detected particles are low-density or high-density using Pyrolysis-GC/MS (Silva et al., 2018). But it is a quick method and can be the best alternatives for routine analysis of microplastics (Dümichen et al., 2017). Another possible advantage of Pyrolysis-GC/MS is that it allows the identification of the chemical composition of the polymer and its associated additives simultaneously (Fries et al., 2013). Moreover, This type of analysis omits the requirement of any pretreatment of the samples (Kusch, 2017). In contrast, Samples with a high amount of impurities and samples with smaller particles (<500µm) do not have applicability to Pyrolysis-GC/MS analysis (Yang et al., 2021). However, only a small volume of samples (5-200 µg) can be analyzed at a time with the machine setup of Pyrolysis-GC/MS -GC/MS (Kusch, 2017). Besides, Some polymers may exhibit identical degradation outcomes and lead to the misidentification of polymer types (Gong and Xie, 2020).

2.4 Abundance and Characteristics of MPs

2.4.1 Factors affecting the occurrence of MPs in river sediment

The abundance of microplastics in river sediment depends on various factors such as Population density, level of urbanization, and anthropogenic activity of surrounding area; precipitation, wind intensity, tidal current, river width, flow velocity, season, and microplastics properties. Thus, the concentration of microplastics varies significantly around the globe (Jiang et al., 2019).

Since rivers receive household sewage, industrial effluent, and agricultural wastewater, the abundance of microplastics has a positive correlation with population size, urbanization, industrialization, recreational, and other human-induced activities(Huang et al., 2020; Nel et al., 2018; Wen et al., 2018; Wu et al., 2020). Though microplastics particles can travel for prolonged distances (Gerolin, 2020), the concentration of microplastics decreases with the distance from the city or industry (Prata et al., 2021). For example, (Jiang et al., 2019) found comparatively high amount of microplastics in the sediment near Lhasa, the capital of the Tibet Autonomous region, high in population and tourist attraction. On the contrary, (Wang et al., 2018) observed an exception of this trend in the sediments of a river network in eastern China, where concentrations of microplastics in the sampling sites near the highly populated region were slightly lower than the average value of all sites.

Low flow velocity promotes sedimentation, where high flow velocity accelerates the mobilization of microplastics in the aquatic environment (He et al., 2020). Thus the flow velocity of a river is negatively correlated with the microplastic concentration in sediment (Tien et al., 2020). This correlation results in low microplastics accumulation during the rainy season (Wu et al., 2020) and high microplastics abundance in the comprehensive portion of the river (Huang et al., 2020). Subsequently, higher microplastics accumulation is observed during winter than summer due to the decrease in flow rate (Nel et al., 2018; Schmid et al., 2020). Again, Extensive rainfall incorporated with high wind intensity and intense wave action associates the entrance of microplastics from sediment to the water column and reduces microplastics concentration in sediment (Amrutha and Warrier, 2020). A study in the Maozhou river illustrated a similar correlation where microplastic concentrations in the sediment during the dry season were 10 to 200 items per kg higher than those observed during the wet season. Notwithstanding, (He et al., 2020) found exceptions to this trend in some sampling sites where microplastic concentrations were higher in the wet season compared to the dry season. Moreover, there is evidence of increasing microplastics abundance after a typhoon both in water column and sediment (Wang et al., 2019).

Accumulation of microplastics in sediment also depends on microplastics properties like density and surface to volume ratio (Wu et al., 2020). High surface to volume ratio and low density enables the polymer to remain in the water column as suspension, whereas low surface to volume ratio and high density promotes deposition of polymer in the riverbed (Lin et al., 2018; Liu et al., 2021; Wu et al., 2020).

2.4.2 Characteristics of MPs

Microplastics can be categorized based on the following characteristics- Shape, size, color, and chemical composition (Fred-Ahmadu et al., 2020). The overview of our investigation on microplastics characteristics is summarized in Table B.3.

2.4.2.1 Shape

Shape of microplastics can be controlled by various factors like source, deterioration process, and retention time (Yang et al., 2021). Fiber, film, pellet, foam, and fragment are the most usual shape of microplastics (Ding et al., 2019; Huang et al., 2020; Wu et al., 2020), but some studies included a few additional categories like sheet, sphere (or bead), line and others for the classification of microplastics based on shape (Constant et al., 2020; Fan et al., 2019; Feng et al., 2020).

Fiber is a secondary microplastic, cylindrical in shape, and whose length is significantly higher than its width (Huang et al., 2020; Ngo et al., 2019). It usually originates from synthetic clothes during the washing and manufacturing process of textile goods, fishing nets, ropes, and sacks (Amrutha and Warrier, 2020; Ngo et al., 2019; Yang et al., 2021). Fibers produced from fishing activity can be defined as lines (Dioses-Salinas et al., 2020). Pellet is a primary microplastic which is spherical or elliptical in shape and usually derived from personal care products such as cosmetics, toothpaste, etc. (Huang et al., 2020; Kutralam-Muniasamy et al., 2020; Ngo et al., 2019). Film is a thin, pliable polymer, whereas foam is a soft, light microplastic (Wu et al., 2020). Microplastics with irregular shapes and definite thicknesses are categorized as fragments (Huang et al., 2020). Continuous exposure of large plastic debris to erosion, wear, and UV light may produce fragments (Yang et al., 2021). However, Film, foam, and fragments can originate from wrapping or packaging materials, supermarket bags, milk boxes, tires, pavement materials during the mechanical wearing or chemical degradation process (Kutralam-Muniasamy et al., 2020; Ngo et al., 2019; Wang et al., 2017). Foam is also derived from the insulating material of buildings (Wang et al., 2 017)

Interaction with various organisms depends on the shape of microplastics (Kutralam-Muniasamy et al., 2020). The irregular and angular shape of fragments provide a suitable surface for the attachment of microorganisms which accelerates the sedimentation process and increases the removal efficiency of fragments in WWTP (Ngo et al., 2019). However, this phenomenon can severely affect the tissue of microorganisms in the natural environment (Kutralam-Muniasamy et al., 2020). On the other hand, smooth surface and significantly higher length to width ratio galvanize fibers to escape from WWTP and cause less histopathological damage to microorganisms (Kutralam-Muniasamy et al., 2020; Ngo et al., 2019)

Fiber is found to be the predominant shape of microplastic in river sediment in most of our reviewed studies (Jiang et al., 2019; Liu et al., 2021; Tien et al., 2020). However, in the Nakdong River, South Korea, fragments was detected as the most abundant shape and contributed to almost 84% of the total microplastics, which trend is similar to some other studies (Constant et al., 2020; Eo, 2019; Rodrigues, 2018). In Shanghai, China, the most dominant shape was spheres and accounted for 88.98% of the total number of microplastics observed (Peng et al., 2018). In Pearl river catchment, China, and Brisbane river, Australia, the most common shape of microplastics were sheets and films, respectively (Fan et al., 2019; He et al., 2020).

2.4.2.2 Size

The probability of being ingested and the pathway of microplastics largely depend on its size (Amrutha and Warrier, 2020; Yang et al., 2021). Due to high specific surface area, biofouling is more likely to occur in small-size microplastics that fasten their deposition in the river bed (Liu et al., 2021; Wang et al., 2018). So, larger microplastics can migrate longer distances compare to smaller ones. In addition, larger microplastics pose more threat to the environment as it is less likely to be biodegraded, prevails longer time in the environment and eventually converts into small-sized microplastics and nano-plastics (Kutralam-Muniasamy et al., 2020). But smaller particles are more bioavailable to benthic organisms and can be transmitted to the terrestrial food web (Dioses-Salinas et al., 2020). Different studies have detected microplastics of various size ranges, but small size microplastics were dominant in all studies, which indicates high level of weathering and fragmentation of their initial product (Feng et al., 2020; Huang et al., 2020). For example, in the rivers of the Tibet Plateau, 70% of the total microplastics were found to be less than 1mm(Jiang et al., 2019). A similar trend was observed in the middle-lower Yangtze river basin, where microplastics ranges from 0.25-1mm were the most abundant (Su et al., 2018). However, in the Wen-Rui Tang River, microplastics ranges from 20-300 μm were predominant and contributed to 84.6% of the total microplastics (Wang et al., 2018).

2.4.2.3 Color

Colored microplastics are more likely to be mistaken for food and ingested by organisms (Eo, 2019; He et al., 2020; Wu et al., 2020). Moreover, like shape, color can indicate initial sources of microplastics (Eo, 2019; Yang et al., 2021). For example, Transparent microplastics usually originate from plastic bags, bottles, cups, fishing nets, and other disposable plastic accessories (Di and Wang, 2018; Kutralam-Muniasamy et al., 2020). In contrast, fabric, packaging material, cosmetics, and various colored consumer products can be the potential source of colored microplastics (Di and Wang, 2018; He et al., 2020; Yang et al., 2021). Since the color of microplastics can be bleached out during the sample preparation and even in the natural environment during the photodegradation process, careful approach is required to identify the source of microplastics based on color (Fan et al., 2019; Yang et al., 2021). Furthermore, during sample extraction and purification process, some microplastics can be eroded and result in the underestimation of transparent microplastics during identification (He et al., 2020).

Microplastics are recommended to classify into four colors – Colorless or transparent, black, white, and colored (Yang et al., 2021). However, some studies have also sub-grouped the colored microplastics into yellow, green, blue, red, etc. categories (Jiang et al., 2019; Wen et al., 2018). In most of our reviewed studies, transparent microplastics were found to be predominant. For example, transparent microplastics contributed to 45.69% of the total number of microplastics in the Tibetan Plateau (Feng et al., 2020). However, white particles were also found to be the most abundant in some studies. For instance, the contribution of white spheres in Shanghai, China were almost 90% (Peng et al., 2018). In contrast, yellow particles were most dominant in the Pearl River and accounted for 36.2% of the entire microplastics (Lin et al., 2018).

2.4.2.4 Chemical Composition

Chemical composition is one of the most fundamental characteristics of microplastics (Zhang et al., 2020). At present more than 30 types of microplastic polymers have been identified in different studies (Ngo et al., 2019). Among them Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Poly(ethylene-propylene) Copolymer, Polyethylene Terephthalate (PET), Polyester (PES), Polyvinylchloride (PVC), Vinyl Acetate Copolymer (VC/VAC), Polyamide (PA), Cellulose, etc. are noteworthy. PP, PE, and PET usually originate from packaging material, plastic bags, containers, agricultural films, conduits, cords, automobiles, and domestic accessories, etc. (Kutralam-Muniasamy et al., 2020; Liu et al., 2021; Tien et al., 2020). On the contrary, fabrics, lines and furniture fillers, etc. are the potential source of PA and PES (Tien et al., 2020).

Floatation and sedimentation of polymers in the aquatic environment largely depend on chemical composition (Ngo et al., 2019). High-density polymers are likely to be deposited in sediment, so concentration is expected to be higher in the sediment than water (Eo, 2019). Despite low density, PE and/or PP were detected as the most abundant polymer type in most of our reviewed studies. For instance, in the sediment of the Haihe River, PE and PP account for 49.3% and 32.9% of the total microplastics, respectively (Liu et al., 2021). Moreover, PP (38%) dominated the types of polymers observed in downstream of West River and followed by PE (27%), PS (16%), PVC (6%), and PET (4%) (Huang et al., 2020). Biofouling on the surface of PE and PP that influenced them to sink in the river bed may be the potential cause of this (Huang et al., 2020). Other than PP and PE, polymer types varied considerably in different studies. For example, PES (33%) and PA(24%) were predominant in the Yangtze River basin and Ebro river sediment, respectively. (Su et al., 2018). Typical surface textures of the MPs by SEM-EDS analysis are shown in Figure 2.5

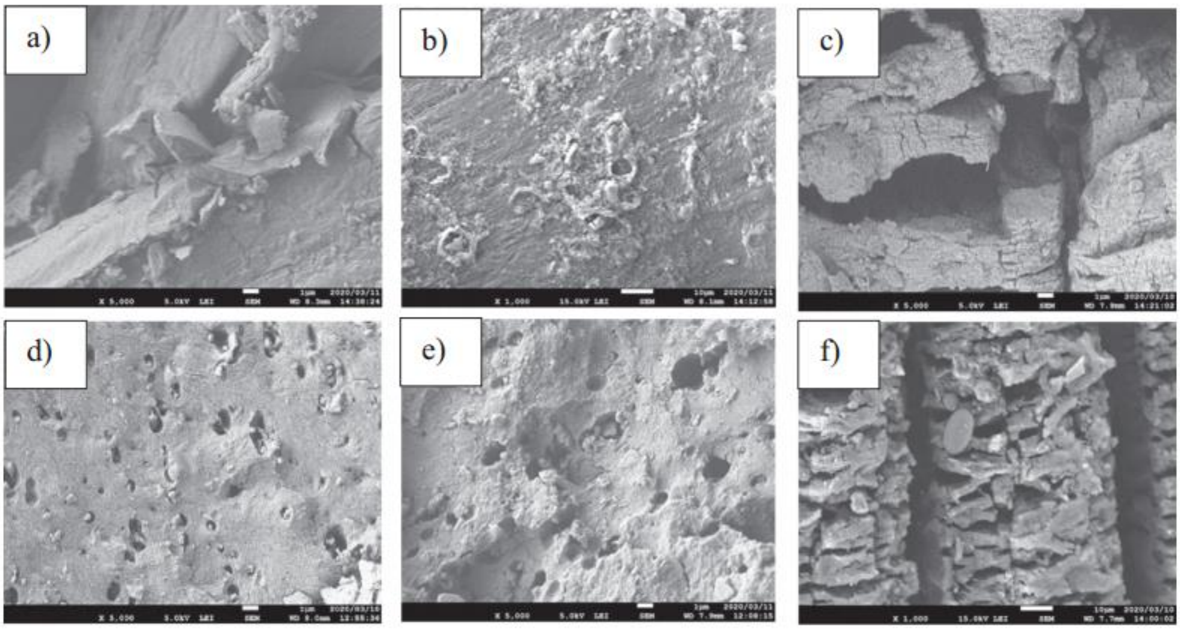


Figure 2.5:Surface textures of the selected MPs by SEM-EDS analysis. a) PE fragment b) PE film c) PE fragment d) & e) PP fragment f) PE fiber. (Kabir et al., 2022)

2.5 Research on the detection and assessment of microplastics pollution in Bangladesh

In July 2022, “microplastic Bangladesh”, “microplastics in Bangladesh”, “microplastic pollution in Bangladesh”, “micro debris”, or “micro plastic fragments” were used as keywords to find out research on microplastics pollution in Bangladesh from Web of Science, Science Direct, and Google Scholar. A total of 18 studies were found. The existing studies on microplastics pollution in Bangladesh was divided into six broad groups based on regions of analysis and sample types: 1) Coastal sediment/water, 2) Urban water, sediment and fish, 3) Estuary sediment/water, 4) Marine/freshwater fish and shrimp species, 5) Salt farms/edible salts, and 6) Ship breaking yard soil. A compilation of results from different studies, sampling method, separation technique, characterization process, abundances and characteristics of microplastics is summarized in Table 2.1.

Table 2.1: Summary of the studies and findings on microplastic pollution in Bangladesh.

Region /Sample Type	Study area	Sampling method	Separation technique	Characterization technique	Abundance of microplastics	Dominant characteristics of microplastics				Ecological Risk Index (PLI, PHI and ERI)	References
						Size	Shape	Color	Polymer		
Coastal/ Sediment	Cox's Bazar	Samples collected from the upper 2 cm layer of beach during low tide at 21 points by a 0.5 m × 0.5 m wood quadrat	H_2O_2 digestion and density separation	Optika Binocular microscope and FT-IR	8.1 ± 2.9 particles/kg	1500–3000 µm	Fragments (64%)	Yellow/ Orange (38%)	PP (50%)	Not assessed	Rahman et al., 2020
	Cox's Bazar	Upper sand layer by a metal quadrat; A total of 24 samples were collected from eight stations, each having triplicates.	H_2O_2 digestion and density separation	Stereomicroscop	209.1 ± 9.09 particles/kg sediments (Inani)	1000–1500 µm	Fibers (53%)	Purple (18%)	FTIR not Performed	Not assessed	Hossain et al., 2021
	Cox's Bazar	Samples (4–4.5 kg) of wet sediment grabbed from 30 cm^2 area at depths of 2–5 m below water surface; A total of 20 samples were collected from parallel to shoreline	Sieving by a series of brass sieves with sizes of 5, 2.5, 1.25 and 0.625 mm	Visual observation, SEM, and ATR-FTIR	100,000 particles/kg	< 1000 µm	Fibers (55%)	White (59%)	Rayon (27%)	Not assessed	Tajwar et al., 2022
	Saint Martin's Island	A total of 12 sediment samples have been collected from a depth of 2–5 m using stainless-steel scrapper from an area of around 30 cm^2 resulting in one bulk sample of 1.5–2 kg	Sieving by a series of brass sieves with sizes of 5, 2.5, 1.25 and 0.625 mm, H_2O_2 digestion and density separation	Stereomicroscope and ATR-FTIR and	208 items/kg	500–1000 µm	Fibers (50%)	White (58%)	Rayon (32%)	Not assessed	Tajwar et al., 2022
	Kuakata	A total of 24 sediment samples were collected from eight sampling points, each having triplicates, Surface sand samples (top 5 cm) were collected using a metal quadrate (30 cm × 30 cm).	H_2O_2 digestion and density separation	Stereomicroscope and FTIR with KBr pellet technique	232 ± 52 items/kg	1000–5000 µm	Fibers (55%)	Transparent (40%)	PET (45.5%)	PLI assessed	Banik et al., 2022
Urban /Water	Dhaka (Dhanmondi, Hatirjheel and Ramna Lakes, Buriganga and Turag rivers)	A sampling net with pore size less than 0.3-mm was used for collection of water samples from 3 lakes and 2 peripheral rivers.	Wet sieving through 4.75-mm (No. 4) and 0.3-mm (No. 50) stainless steel mesh sieves, H_2O_2 digestion and density separation	Magnifying glass	0.49–9.48% of total solid	-	-	-	FTIR not Performed	Not assessed	Shadia et al., 2022
Urban/ Water and Sediment	Dhaka (Buriganga river)	A total of 12 sediment samples have been collected from the shore using stainless steel scoop and a stainless-steel mug and a 300 µm stainless steel sieve (Fritsch, Germany) were used to collect 12 surface water samples	H_2O_2 digestion and density separation	Microscopic, FTIR spectroscopic, FE-SEM and ED-XRF analysis.	17.33 ± 1.53 to 133.67 ± 5.51 Items/Kg of Sediment 4.33 ± 0.58 to 43.67 ± 0.58 Items/L of Water	1000–3000 µm	Fragment	Red and Transparent	PP and PE	PLI assessed	Islam et al., 2022

Region /Sample Type	**Study area**	**Sampling method**	**Separation technique**	**Characterization technique**	**Abundance of microplastics**	**Dominant characteristics of microplastics**				**Ecological Risk Index (PLI, PHI and ERI)**	**References**
						Size	**Shape**	**Color**	**Polymer**		
Urban/ Water, Sediment and Fish	Dhaka (Dhanmondi, Gulshan, and Hatir Jheel).	Water, sediment and fish samples were collected from three lakes Water: 5L water was collected using a steel bucket within 0-10 cm from the surface and 3 replicates per location Sediment: 1 kg of wet sediment was collected and 3 replicates per location Fish samples: A total of 7 species (n=90) were collected using a net within the depth of 1-10 meters	H_2O_2 digestion and density separation	Stereo Microscope and ATR-FTIR	Water: 0-9 items/L Sediment: 0-16 items/kg Fish: 0-17 items/individual; 0-4.88 items/g in the gastrointestinal tract (GIT)	-	Water: film (40.91%) Sediment: Fiber (30.55%) Fish: Pellets (29.28%)	-	Water: HDPE (60%) Sediment: HDPE (42.85%) Fish: HDPE (40%)	Not assessed	Mercy et al., 2022
Urban/Soil	Dhaka (Aminbazar Sanitary landfill sites)	A total ten samples Unmixed soil samples collected from landfill sites were collected from the five corresponding areas in two different depths, topsoil and 0–20 cm depth	H_2O_2 digestion, and density separation with NaCl solution	Stereomicroscope and FTIR with KBr pellet method	Three out of 10 samples were identified to contain microplastics	-	Fiber	-	HDPE, LDPE and CA	Not assessed	Afrin et al., 2020
Estuary/Sediment	Karnaphuli River	Samples were collected using an Ekman dredge from 30 locations	H_2O_2 digestion, and density separation	Stereomicroscope and ATR-FTIR	22.29–59.5 item/kg of dry weight (DW) of sediments	1000–5000 µm	Films (33.32%)	White (19.25%)	PET (27.78%)	PLI, PHI and ERI were assessed	Rakib et al., 2022
Marine/Fish species	Northern Bay of Bengal (Chittagong)	A total 75 fresh samples of three species were collected from commercial fishing trawlers (Different hauling times, hauling speeds at different depths) in the northern coast of the Bay of Bengal	H_2O_2 digestion and density separation with NaCl solution	Binocular Microscope and µ-FTIR	The abundance of microplastics ranged from 0.37 to 1.55 particles/gram GIT	500–1000 µm (37%)	Fibers (50%–55%)	White/transparent (26%–68%)	Polyamide (75%)	Not assessed	Hossain et al., 2019
Marine/Penaeid shrimp	Northern Bay of Bengal (Chittagong)	A total of 50 Tiger shrimp samples collected from offshore trawlers with haul time of 2–3 h and an average hauling speed of 4 knots at about 40–60 m depth. A total of 100 Brown shrimp samples collected from set bag nearshore (2–3 m depth)	H_2O_2 digestion and density separation with NaCl solution	Binocular Microscope and µ-FTIR	From 3.40 to 3.87 (particles/per gram GT)	1000–5000 µm (32%)	Fibers {57% (Tiger shrimp)–32% (Brown shrimp)}	Black {57% (Tiger shrimp)–32% (Brown shrimp)}	Polyamide (59%)	Not assessed	Hossain et al., 2020a
Marine/Fish species	Northern Bay of Bengal (Kuakata)	A total of 100 individual fish, 10 per species, were collected from a seashore fish market.	H_2O_2 digestion	Binocular Microscope, ATR-FTIR and SEM	From 2.11 to 2.29 (particles/per gram GT)	< 500 µm (85%)	Fibers (53.4%)	Green (39%)	Polyethylene (55%)	Not assessed	Ghosh et al., 2021

Region /Sample Type	Study area	Sampling method	Separation technique	Characterization technique	Abundance of microplastics	Dominant characteristics of microplastics				Ecological Risk Index (PLI, PHI and ERI)	References
						Size	Shape	Color	Polymer		
Freshwater/Fish species	Rivers, lakes, canals surrounding Dhaka city	A total of 48 fishes from eighteen species (2–6 individuals of each species) were purchased from two big fish markets named the Ashulia and Savar fish market.	Alkali digestion with 10% KOH	Binocular Microscope, FTIR with KBr pellet method and SEM	From 0.04 to 6.3 particles/kg body weight	< 500 µm (36%)	Fibers (75%)	Transparent (43%)	High density polyethylene (40%)	Not assessed	Parvin et al., 2021
Freshwater/Fish species	Jamuna River	In total, 45 individuals representing seven species with 20.74±8.65 cm average length were collected by 5 mm mesh nets from Bangabandhu Bridge, Tangail District to Chauhali Upazila, Sirajganj District	HNO_3 and NaOH digestion and density separation with NaCl solution	sky-basic wireless digital microscope	1.80±1.65 particles (SD) per total fish	-	Fiber (70%)	Black (27%)	FTIR not Performed	Not assessed	Khan et al., 2021
Salt farms, refineries and markets/Edible Salts	Cox’s Bazar	Raw salt samples (21) were collected from salt farms in Cox’s Bazar and refined salt samples (8) were collected from local salt refineries while super refined salt samples (3) were collected from the market.	H_2O_2 digestion	Omron Microscope	Raw (unrefined) salt: 2105 MPP/kg; refined Salts: 283 MPP/kg .	<330 µm	Irregular	Black (24%)	FTIR not Performed	Not assessed	Zafar et al., 2020
Ship Breaking Yards and control samples at Chittagong/ Soil	Bhatiary and Kattali Sea Beach at Chittagong	In total, 18 soil samples were collected from five Ship Breaking Yards (SBYs) in Bhatiary, Chittagong and a control sample was collected from Kattoli Sea Beach. In each yard, samples were taken from three zones.	H_2O_2 digestion and density seperation	Microscope and FTIR	SBY: 217 MP particles per kg Control: 127 MP particles per kg	300–1000 µm	SBY: Fragments (40%) Control: Fiber (63%)	Transparent (22%)	-	Not assessed	Haque et al., 2020
Sea beach/sea salts	Cox's Bazar	Thirteen commercial sea salts were collected from different supermarkets and local markets of Bangladesh	H_2O_2 digestion	Stereo microscope, FTIR and SEM-EDX	2676 MPs/kg	1000–5000 µm (49%)	Fiber (59%)	white/transparent and blue	Nylon	Not assessed	Parvin et al., 2021
Bay of Bengal/ Salt pans	Maheshkhali Channel	Sea salt samples were collected from eight representative salt pans; 500 g of salts were collected using a metal spoon at each site	H_2O_2 digestion	Stereomicroscope, FT-MIR-NIR	74.7 to 136.7 particles/kg	500–1000 µm (40%)	Fragments (48%)	White (37%)	PET (48%)	PHI was assessed	Rakib et al., 2022

CHAPTER 3 METHODOLOGY

3.1 General

The main objective of this research was to investigate the abundance and characteristics of microplastic in river bed sediment around Dhaka city (Buriganga, Turag and Balu rivers).

This Chapter presents the methods used in this research to carry out the laboratory experiments for analysis of microplastics with step-by-step procedure followed for identification and characterization of Microplastics as well as assessment of ecological risk indices. Flow chart of key research activities is shown in Figure 3.1.

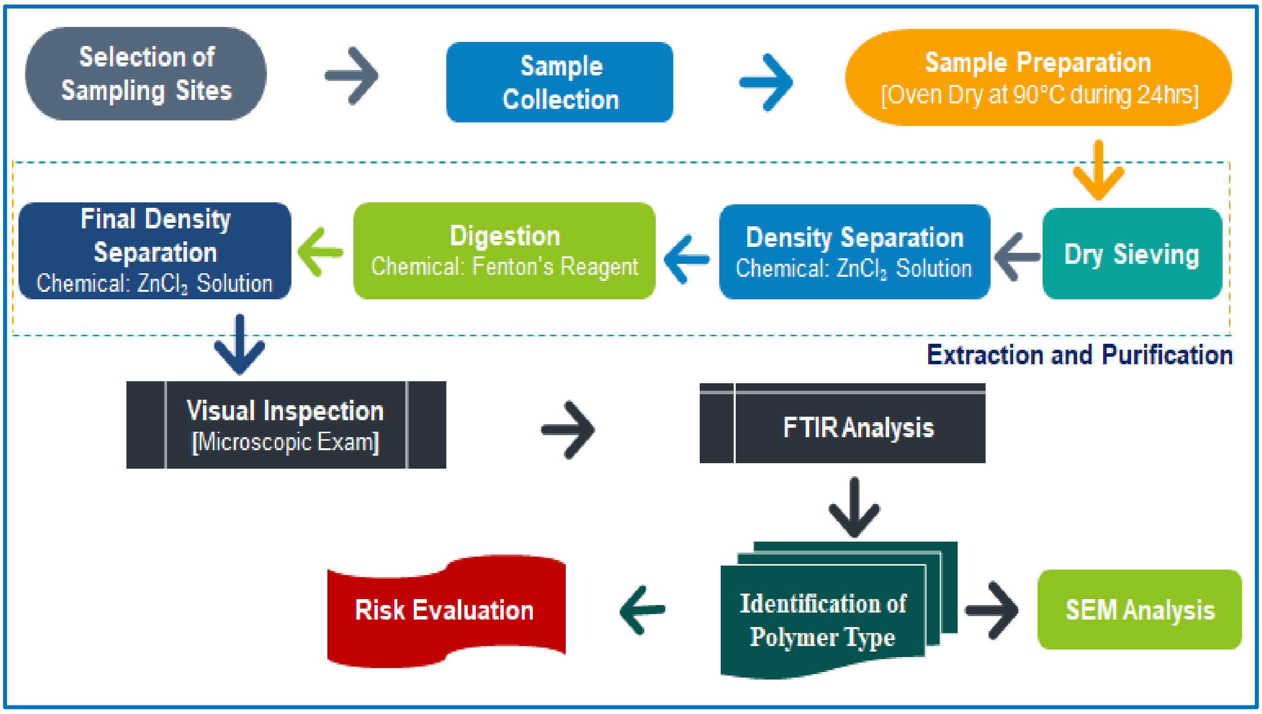


Figure 3.1: Flow chart of key research activities.

3.2 Study area and Selection of Sampling Location

The study was conducted in three (3) peripheral river of Dhaka city like Buriganga (BR), Turag (TR), and Balu (BaR). The length of these freshwater streams is as follows: BR: 23 km, TR: 36 km, and BaR: 15 km. The subbasins of the rivers were generated from Digital Elevation Model (DEM) using ArcGIS v.10.8 (Esri, USA). The subbasins of BR, TR, and BaR have a catchment area of 251.50 km^2, 290.56 km^2 and 463.88 km^2 respectively.

In total, 28 sampling points from the BR (n=11), TR (n=14) and BaR (n=3) were selected across the rivers considering the land-use patterns and sources of pollution as shown in Figure 3.2. The details of sediment sampling location are shown in Table 3.1. Land-use characteristics information of Dhaka city and its adjacent area were obtained from the US Geological Survey (USGS). Point sources (Residential, commercial and industrial areas) dominated most of the sampling stations of BR, except BR10, which was influenced by both point and non-point sources (agricultural and greenfield lands). Apart from sampling stations TR8-TR10 (dominated by point sources) and TR12 (mostly occupied by non-point sources), the rest of the sampling points of TR were affected by both point and non-point sources. The sampling station BaR1 was comparatively less polluted and mostly influenced by agricultural lands and open spaces, however, BaR2 had high influence of point sources. The station BaR3 was the confluence of the Shitalakshya and Balu Rivers.

Table 3.1: Details of riverbed sediment sampling locations.

SL. NO.	Assigned ID	GPS Coordinates	Site Description
01	BR1	23.664859° 90.452726°	Downstream of pagla STP (residential, commercial and industrial area)
02	BR2	23.679284° 90.439381°	Upstream of pagla STP (residential, commercial and industrial area)
03	BR3	23.690331° 90.425369°	Faridabadh residential area, buriganga bridge near fatullah, postogola govt. modern flour mill
04	BR4	23.699379° 90.417263°	Downstream of sadar ghat, sluice gate near buriganga river, farashganj bridge
05	BR5	23.709795° 90.401527°	Commercial area, sawari ghat, babu bazar, salimullah medical college
06	BR6	23.710026° 90.390533°	Downstream of sultanganj residential and commercial area, kamrangi char
07	BR7	23.740877° 90.351158°	Boshila residential area, bangladesh eye trust hospital
08	BR8	23.751012° 90.330164°	Boshila residential area, brick firm
09	BR9	23.769175° 90.344659°	Residential area: baitul aman housing society, sunibir housing
10	BR10	23.777804° 90.337171°	Downstream of gabtoli sweeper colony, BIWTA landing station
11	BR11	23.783858° 90.335702°	Gabtoli cattle market, amin bazar landing station, gabtoli bridge
12	TR1	23.786274° 90.338190°	Golaptak mix zone area, boro bazar, boro bazar ghat

SL. NO.	Assigned ID	GPS Coordinates	Site Description
13	TR2	23.799784° 90.343166°	Residential and homestead plants area: Turag city, bangladesh national zoo, diabari boat yard
14	TR3	23.826958° 90.342968°	Residential and planted garden: eastern housing, botanical garden, tamanna family park, s4 sluice gate
15	TR4	23.854818° 90.341898°	Downstream of RAJUK residential area (effect of ashulia industrial area).
16	TR5	23.890476° 90.359335°	Ashulia ferry ghat, ashulia landing station, ashulia bus stop (effect of ashulia industrial area)
17	TR6	23.893522° 90.362811°	Industrial and residential area (jamaldia, tongi)
18	TR7	23.898066° 90.383805°	Industrial and residential area, kathaldia ghat, greenland hospital
19	TR8	23.880292° 90.393299°	Industrial, residential and hospital area: Shaheed mansur ali medical college and hospital, tongi bishwa ejtema mydan, near uttara sector 11
20	TR9	23.881708° 90.405556°	Mixed zone: tongi bridge, sawdagar stone mill, arichpur residential area.
21	TR10	23.886367° 90.416720°	Effect of industrial area, tongi nodi bondor
22	TR11	23.898398° 90.435431°	Effect of industrial area, radix garments
23	TR12	23.883734° 90.460593°	Agricultural land and open plot for future development near kumutkhola baily bridge
24	TR13	23.861912° 90.474911°	Agricultural land and open plot for future development
25	TR14	23.837315° 90.477250°	Effect due to construction work of 300 ft purbachal road: boalia bridge, balu river, purbachal express highway
26	BaR1	23.796113° 90.481048°	Beraaid residential area, agar para mosjid, A K H rahmatullah stadium
27	BaR2	23.762079° 90.482599°	Open area for future development, rampura khal.
28	BaR3	23.726954° 90.500132°	Confluence of shitalakshya and balu river, karim jute mill

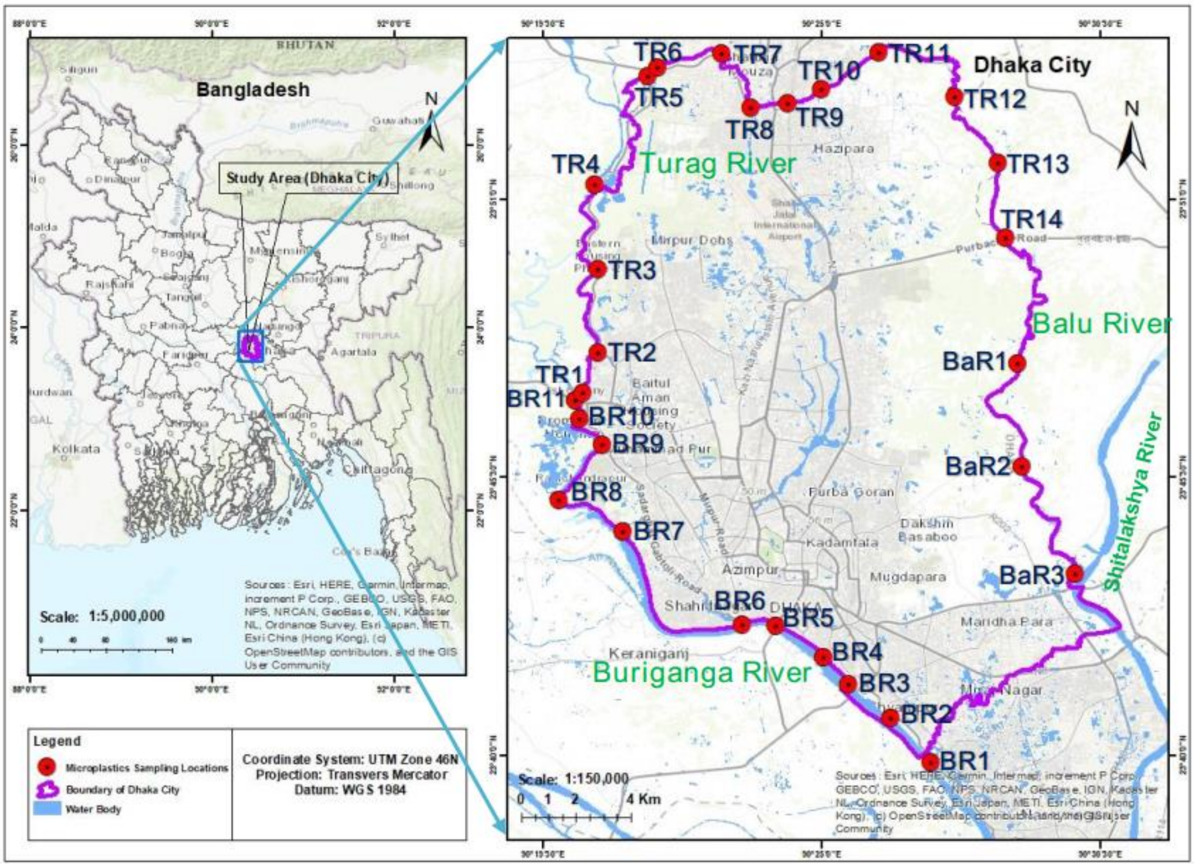


Figure 3.2: Locations of riverbed Sediment Sampling

3.3 Sample Collection

The river samples were collected during dry season. The BR River samples were collected on March 26, 2021 while the samples from the TR and BaR were collected on March 28, 2021. A total of 1 kg of riverbed sediment was sampled, 5-10 m away from the shoreline using an Ekman grab sampler (15×15×15 cm) (Figure 3.3) from top 10 cm of the riverbed at each sampling station. Samples were then transferred immediately into aluminum containers, sealed, and transported to IUT laboratory for subsequent analysis. Samples were preserved at 4° C for further analysis. Figure 3.4 shows some photographs taken during sediment sampling from the rivers.

Figure 3.3: Ekman grab sampler used for sediment samples collection in this study.

Figure 3.4: Photographs taken during sediment sampling from the rivers.

3.4 Sample processing and extraction of MPs

The methodology for the extraction of MPs was designed based on the following (Crew et al., 2020; Frias et al., 2018; Rodrigues et al., 2018) with necessary adjustments. In brief, two-step density separation was employed to remove sediment and other non-organic impurities, and wet peroxidation was performed to discard natural organic matters from the sediment samples. Sediment samples were dried in an oven at 65°C for approx. 24 hours to avoid the influence of humidity. Solids that passed through 5 mm sieve and retained on 0.1 mm sieve were transferred to a beaker and rest of the materials were removed. Further, 500 mL of aqueous $ZnCl_2$ solution was added with 500 gm of dried sample for primary density separation. The mixture was allowed to settle down overnight after vigorous mixing with a spatula. Then, the supernatant was again passed through 0.45μm Pore membrane filter. The extracted particles were then heated in an oven and dried at 65°C. The $ZnCl_2$ solution facilitated the separation of microplastics with relatively high-density polymers, such as PVC (1.16–1.41 g/mL), PET (1.38–1.41 g/mL), etc., in a comparatively cost-effective way (Xu et al., 2020).

In this study, aqueous 0.05 M Fe (II) solution (20 mL) and 30% hydrogen peroxide (20 mL) were added to the beaker containing extracted particles for Wet Peroxide Oxidation (WPO). After keeping the mixture at room temperature for 10 minutes, it was heated at 65° C on a hotplate. The beaker was moved from the hotplate as soon as gas bubble appeared on the surface. When the boiling stopped, it was heated for another 30 minutes. The steps were repeated until no organic matter was visible and each time 20 mL of 30% hydrogen peroxide were added. Final density separation was performed afterward following the similar procedure of preliminary density separation. However, reduced volume of aqueous $ZnCl_2$ solution (150 mL) was used in this step. Figure 3.5 shows some photographs of laboratory analysis.

Figure 3.5: Photographs of the laboratory analysis

3.5 Microplastics identification, quantification, characterization and data analysis

Extracted MPs particles were visually inspected under a Stereo Zoom microscope (SLX-3, Optika, Italy) with standard magnifications from 7x to 45x and categorized based on their sizes, shapes, and colors (Witte et al., 2014; Hidalgo-Ruz et al., 2012; Witte et al., 2014). A digital camera (C-B5, Optika, Italy) was incorporated with the microscope, and the particle size was directly measured utilizing the OPTIKA Proview digital camera software. The total mass concentration of Microplastics at each sampling station was measured by using an analytical balance (XA 210.4Y, Radwag, Poland; Readability: 0.01mg). The polymer composition of the isolated particles was investigated by Fourier Transform Infrared Spectroscopy (FT-IR Spectrum Two, PerkinElmer C110303, UK) with Attenuated Total Reflection (PerkinElmer UATR Two) (Figure 3.6). PerkinElmer Spectrum 10 Spectroscopy Software was used to collect the spectrum data. Background scans were performed before each MP measurement.

Each particle was scanned individually with infrared wavenumbers ranging from 4000 cm^{-1} to 400 cm^{-1} and 10 accumulated scans were taken to obtain 16 cm^{-1} resolution spectra. Finally, the generated FT-IR spectra were compared with Wiley's KnowItAll Spectral Libraries 2021 to identify polymer type. Scanning Electron Microscope (SEM), JEOL JSM-6490LA was used to observe the suspected weathered microplastics surface textures. Some suspected weathered and virgin polymers were selected for SEM analysis considering the presence and absence of the carbonyl group. Microsoft® Excel® 2016 MSO (Version 2205 Build 16.0.15225.20028) was used for the calculation purpose of data and IBM SPSS Statistics Version 26.0.0.0 was used for statistical analysis.

Figure 3.6: Photographs of the FTIR analysis of microplastics.

3.6 Quality assurance/quality control

While performing the experiment, the protocols set by (Masura et al., 2015). were followed to ensure quality control measures. The samples were kept sealed with aluminum foil during the entire experiment. To avoid any deformation and degradation of microplastics, the sediment samples were dried in oven at lower temperature (65°C). Any kind of plastic tools and instruments were deliberately avoided and replaced with glassware and metalware to prevent external contamination. Cotton made wears, and nitrile gloves were worn during analysis. All equipment was rinsed thrice with deionized water before use. Three Blank samples with pure water were analyzed simultaneously to measure possible contamination from the experimental procedures. No laboratory microplastic particles were identified from the blank samples. Moreover, extracted microplastics were stored in the glass vials.

3.7 Ecological risk index assessment approach of MPs

The ecological risk of microplastic pollution in each river was assessed in terms of the Pollution Load Index (PLI), Polymeric Hazard Index (PHI), and Ecological Risk Index (ERI) based on the model used in previous studies (Enyoh et al., 2021; Kabir et al., 2021; Rakib et al., 2021; Ranjani et al., 2021; X. Zhang et al., 2020). The formula of Pollution Load Index (PLI) proposed by (Tomlinson et al., 1980) and hazard scores ($\mathrm{S_j}$) (Lithner et al., 2011) of polymers was used in this assessment. The advantage of this model is that it not only considers the environmental impact of individual contaminants in specific locations but also takes into consideration the synergistic effects of several pollutants (Peng et al., 2018).

The Pollution Load Index for each sampling station ($\mathrm{PLI_i}$) was determined from the ratio of MP abundance obtained at station i ($\mathrm{C_i}$) and minimum background abundance of microplastics from the available literature ($\mathrm{C_0}$). However, the lowest MPs abundance in this investigation was used as the baseline concentration ($\mathrm{C_0}$) due to the lack of available background data in similar study methods, sampling procedure and objectives of this study. Then, the Pollution Load Index ($\mathrm{PLI_{river}}$) of rivers was calculated as the n-th root of the multiplication of all $\mathrm{PLI_i}$ in a river.

$$\mathrm{PLI_i} = \frac{\mathrm{C_i}}{\mathrm{C_0}} \text{ ---(i)}$$

$$\mathrm{PLI_{river}} = \sqrt[\mathrm{n}]{\mathrm{PLI_1} \times \mathrm{PLI_2} \times \ldots\ldots\ldots . \times \mathrm{PLI_n}} \text{ ---(ii)}$$

Here, i denotes a sampling station and n denotes the number of sampling stations in each river. Sampling station is polluted once PLI $>$ 1 (Tomlinson et al., 1980).

Furthermore, the concentration of individual polymers at station i ($\mathrm{P_{ji}}$) was divided by $\mathrm{C_i}$ and multiplied by the hazard score of that polymer ($\mathrm{S_j}$). The computed values for all individual polymers were summed to figure out the Polymeric Hazard Index ($\mathrm{PHI_i}$) of station i. The calculation river Polymeric Hazard Index ($\mathrm{PHI_{river}}$) is similar to $\mathrm{PLI_{river}}$.

$$\mathrm{PHI_i} = \sum_{j=1}^{m} \frac{\mathrm{P_{ji}}}{\mathrm{C_i}} \times \mathrm{S_j} \text{--(iii)}$$

$$\mathrm{PHI_{river}} = \sqrt[n]{\mathrm{PHI_1} \times \mathrm{PHI_2} \times \ldots\ldots\ldots. \times \mathrm{PHI_n}} \text{ --(iv)}$$

In equation (iii), j denotes a type of polymer, and m denotes the number of polymers identified at station i.

The ecological risk index at station i ($\mathrm{ERI_i}$) was determined from the multiplication of $\mathrm{PLI_i}$ and $\mathrm{PHI_i}$. The calculation of the river ecological risk index ($\mathrm{ERI_{river}}$) is similar to $\mathrm{PLI_{river}}$ and $\mathrm{PHI_{river}}$.

$$\mathrm{ERI_i} = \mathrm{PLI_i} \times \mathrm{PHI_i} \text{ --(v)}$$

$$\mathrm{ERI_{river}} = \sqrt[n]{\mathrm{ERI_1} \times \mathrm{ERI_2} \times \ldots\ldots\ldots. \times \mathrm{ERI_n}} \text{ -- (vi)}$$

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

The detail methodology followed to carry out the research is presented in Chapter 3, including methodology followed for sample collection, and the experimental set up for the identification and characterization of microplastics. This chapter presents detail results of the laboratory experiments carried out for abundance, characteristics and ecological risks of Microplastics in river sediments around Dhaka City.

4.2 Microplastics abundances, mass concentrations, and distributions by land use

MPs were observed at all of the sampling locations. The abundance of MPs varies from 46 to 534 number particles per kilogram (kg) of dry sediment. The total number of MPs was 4190 particles among 28 sampling locations. The overall average and median MP abundance were 149.64 ± 83.70 n/kg and 140 n/kg. The higher abundance of MP was exhibited by BR (Mean: 165.45 ± 127.87 n/kg Median: 130 n/kg) than TR (Mean: 142.43 ± 37.32 n/kg Median: 158 n/kg) and BaR (Mean: 125.33 ± 68.16 n/kg Median: 120 n/kg) (Figure 4.4). The highest number of MPs particles 534 n/kg were detected at sampling location BR4, which is near the largest river port Sadarghat of Buriganga river and the lowest number of MPs particles were found at sampling location TR12, which is influenced by grassland and empty plots for future development. However, statistically there was no significant difference of MP abundance among the sampling stations (Kruskal Wallis H Test, p-value = 0.585 > 0.05) (Figure 4.1).

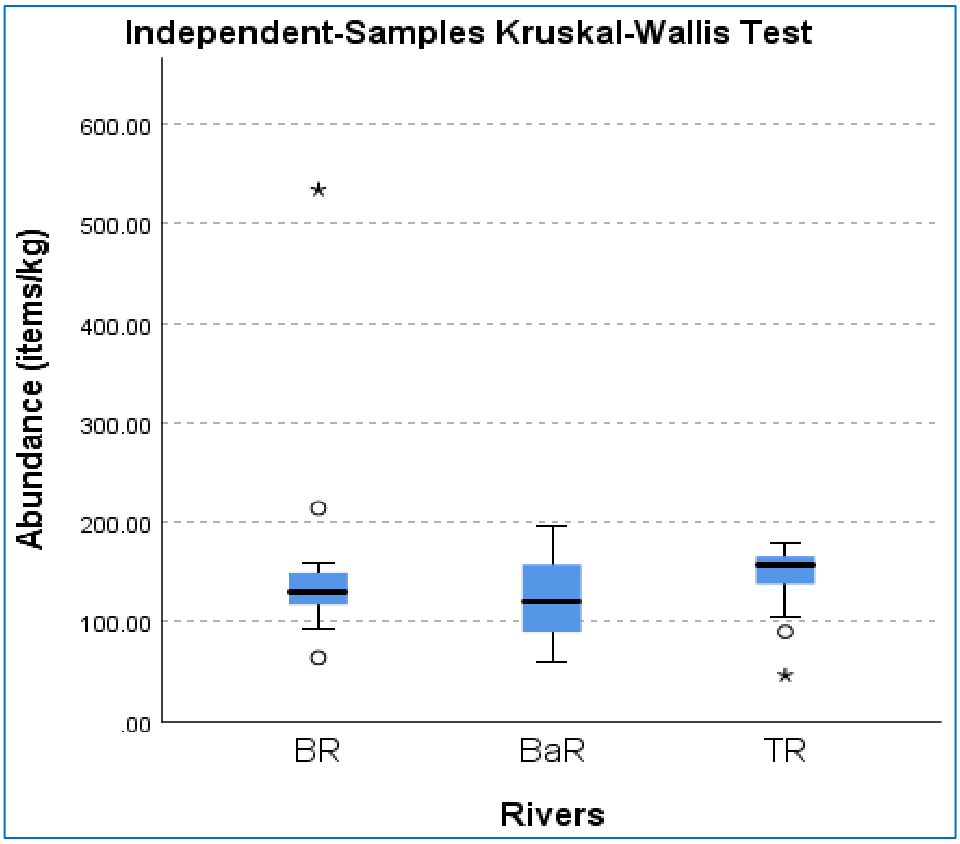


Figure 4.1: Box plot of the Kruskal-Wallis test for MP abundance.

Buriganga River is a higher percentage of mixed (residential, commercial and industrial) land use sources (78.92%) than Turag (64.14%) and Balu River (54.08%) (Table 4.1). Similarly, the average MP abundances were found higher in the Buriganga river than Turag and Balu rivers. On the contrary, the Buriganga river was a lower percentage of agriculture and greenfield land source than others. Thus, MP abundances among the sampling locations represented that mixed land use could cause higher MP pollution than other land use sources, which is consistent with previous studies (Corcoran et al., 2020; Dikareva and Simon, 2019; Tibbetts et al., 2018).

The MPs pollution levels (7.33 ± 1.53 items/kg to 133.67 ± 5.51 items/kg) in shoreline sediment samples of Buriganga river reported by (Islam et al., 2022) is lower than this study, mainly due to variation of sampling location along with other associated factors such as sampling season, sampling methodology, extraction procedure, and identification techniques. The large plastic particles initially deposited to river bank and shoreline, which converted into MPs with time due to weathering action and finally accumulated in riverbed sediment. Hence, shoreline sediment yields lower MPs count than riverbed sediment.

Table 4.1: River basin and land-use information of the studied rivers.

Rivers	Unit	Area	Urban and settlement area	Agricultural and greenfield land	Water Body	Others
Buriganga River (BR)	km^2	251.50	198.49	34.16	16.29	2.56
	%	100.00	78.92	13.58	6.48	1.02
Turag River (TR)	km^2	300.06	192.47	48.91	32.78	25.90
	%	100.00	64.14	16.30	10.92	8.63
Balu River (BaR)	km^2	463.88	250.85	104.24	33.93	74.86
	%	100.00	54.08	22.47	7.31	16.14

The mass concentration of MP varies from 13.56 mg/kg to 430.65 mg/kg with an overall average value 106.52 ± 73.17 mg/kg (Figure 4.4). The average mass concentration among the rivers varies as follows: BR (Mean: 127.13 ± 106.85 mg/kg; Median: 85.34 mg/kg) > TR (Mean: 97.55 ± 43.24 mg/kg; Median: 91.43 mg/kg) > BaR (Mean: 72.76 ± 33.35 mg/kg; Median: 63.27 mg/kg). However, Kruskal Wallis H Test (p-value = 0.560 > 0.05) indicated an insignificant difference in mass concentration among the rivers (Figure 4.2). Also, Mass concentration and abundance has strong positive correlation statistically (Spearman rank correlation, p value = 0.004 < 0.05; $r^2 = 0.528$) (Figure 4.3). The correlation result indicated that the mass concentrations were dependent on numerical abundances. However, BR1 (112 n/kg; 55.38 mg/kg) and TR9 (158 n/kg; 63.71 mg/kg) had a higher number of particles than BR8 (64 n/kg; 155.27 mg/kg) and TR14 (90 n/kg; 203.23 mg/kg) nevertheless BR1 and TR9 had comparatively lower mass concentration than BR8 and TR14 since the mass of MP particles was also dependent on the particle volume and density (Eo et al., 2019). Thus, the mass concentration of the particles not only depends on numerical abundance but also depends on other factors (e.g.: volume, density, etc.). The abundance and mass concentrations of microplastics (MPs) in different sediment sampling points are shown in Table 4.2 and Figure 4.4.

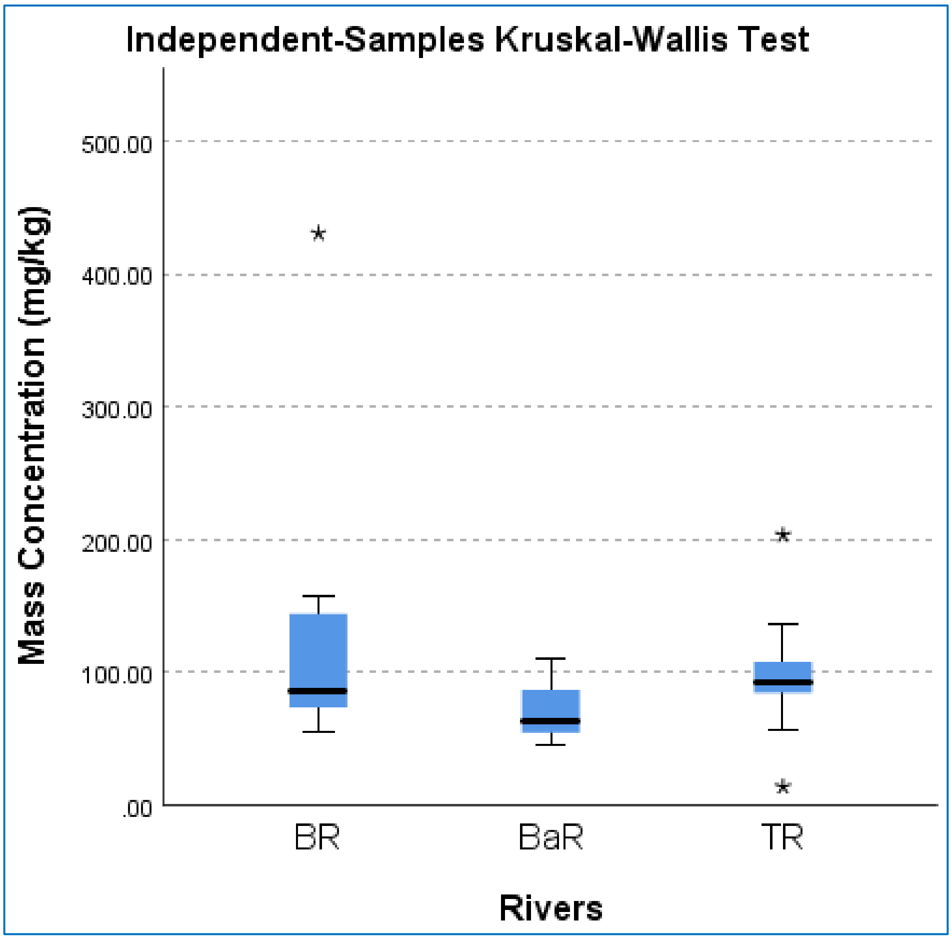


Figure 4.2: Box plot of the Kruskal-Wallis test for mass concentration.

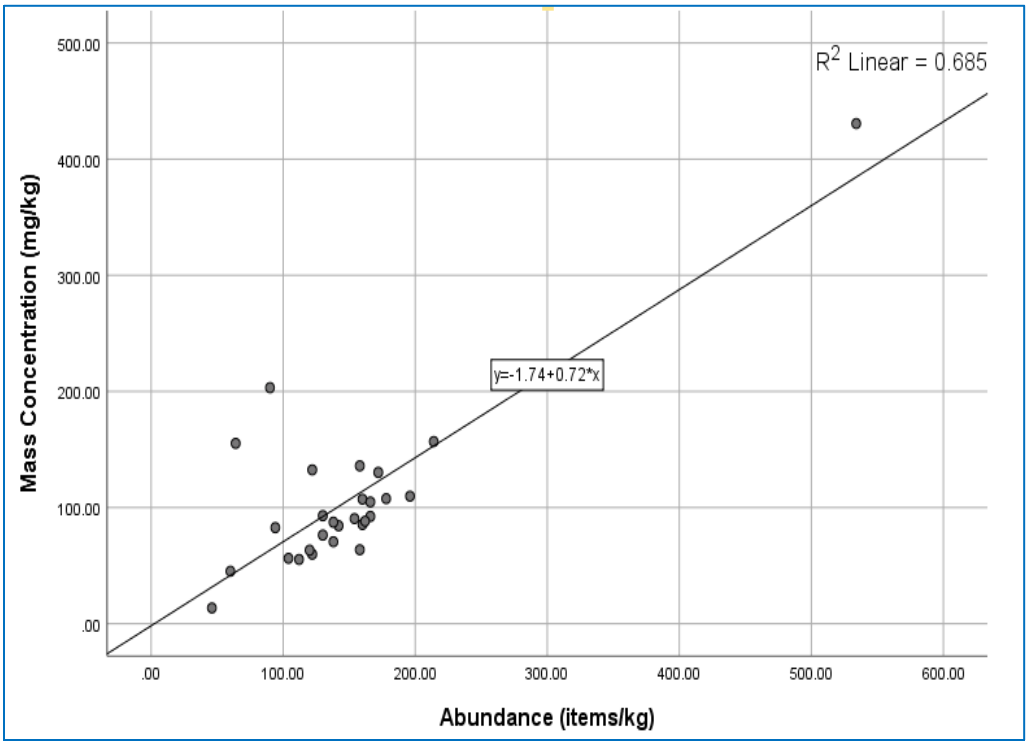


Figure 4.3: Correlation between MPs abundance and mass concentration.

Table 4.2: Abundance and mass concentrations of MPs in different sediment sampling points.

Rivers	Locations	Abundance* (n/0.5 kg)	Abundance (n/kg)	Mass Concentration (mg/ kg)
Buriganga River (BR)	BR1	56	112	55.38
	BR2	47	94	82.74
	BR3	61	122	132.5
	BR4	267	534	430.65
	BR5	107	214	156.85
	BR6	80	160	85.34
	BR7	65	130	93.02
	BR8	32	64	155.27
	BR9	65	130	76.31
	BR10	69	138	70.56
	BR11	61	122	59.82
Turag River (TR)	TR1	89	178	107.69
	TR2	83	166	92.37
	TR3	71	142	84.31
	TR4	80	160	107.27
	TR5	79	158	135.93
	TR6	77	154	90.49
	TR7	83	166	104.83
	TR8	81	162	88.29
	TR9	79	158	63.71
	TR10	86	172	130.29
	TR11	69	138	87.39
	TR12	23	46	13.56
	TR13	52	104	56.34
	TR14	45	90	203.23
Balu River (BaR)	BaR1	30	60	45.19
	BaR2	60	120	63.27
	BaR3	98	196	109.83
Total		**2095**	**4190**	**2982.43**

*Number of Extracted MPs

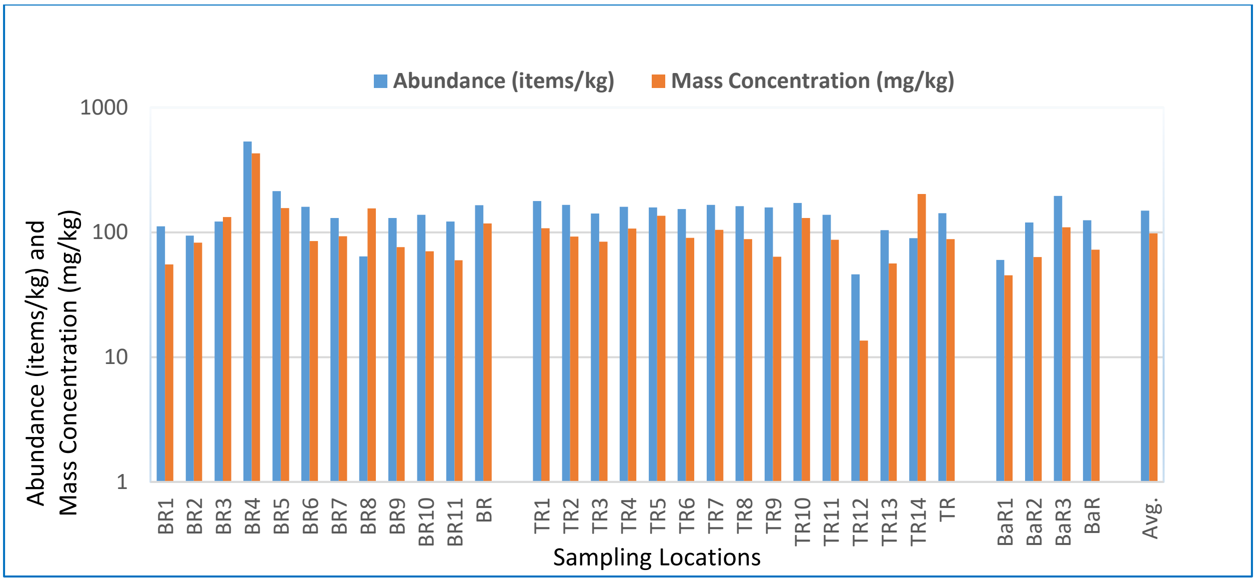


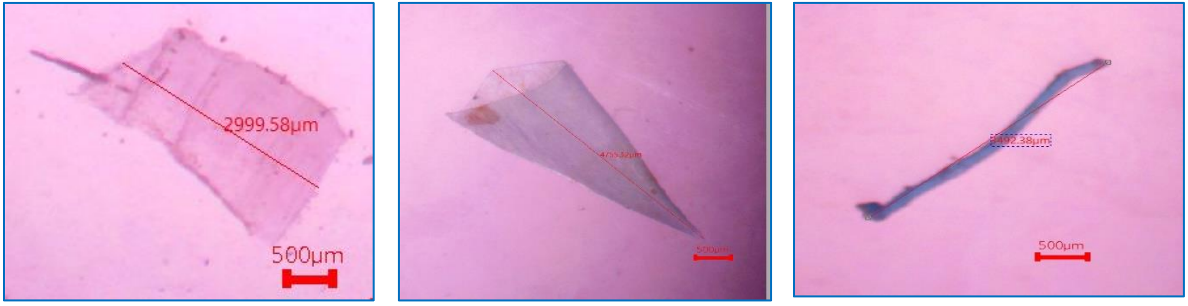
Figure 4.4: Abundance and mass concentrations of microplastics (MPs) in different sediment sampling points.

4.3 Characteristics of Microplastic

4.3.1 Shapes

The observed MPs particles were shorted into three following shapes: films, fragments, and fibers (Figure 4.5). Films (53.89%) were the most abundant shapes followed by fragments (37.57%), and fiber (8.54%). The highest proportion of films (55.27%) and fragments (40.43%) shape were in Turag river and Buriganga river respectively in comparison with other rivers. However, similar shapes exhibited almost similar proportions in different rivers. The number of films and fragments particles was the same at BR8 of Buriganga river and at TR2 of Turag river, which were influenced by residential areas. The highest proportion of films (78.26%) was observed at Industrial affected sampling location TR11 of Turag river. Overall the findings were that films and fragments were higher proportions than other shapes of MPs extracted from riverbed sediment samples, which is consistent with the result of previous studies conducted by (Islam et al., 2022; Kabir et al., 2020; Shruti, 2019; Xu et al., 2020). Figure 4.6 illustrates the shape-based distribution (%) of microplastics extracted from different sediment sampling points.

a) Fragment b) Film c) Fragment



d) Film e) Film f) Fiber

Figure 4.5: Microscopic views of microplastics collected from sediment sampling points.

Table 4.3: Numbers of various shaped MPs in different sediment sampling points.

Locations	Fragment	Film	Fiber
BR1 (112)	30	68	14
BR2 (94)	44	36	14
BR3 (122)	42	68	12
BR4 (534)	190	252	92
BR5 (214)	84	120	10
BR6 (160)	66	88	6
BR7 (130)	56	68	6
BR8 (64)	30	30	4
BR9 (130)	52	72	6
BR10 (138)	48	82	8
BR11 (122)	38	72	12
BR (1820)	**680**	**956**	**184**
TR1 (178)	72	82	24
TR2 (166)	76	76	14
TR3 (142)	52	56	34
TR4 (160)	54	82	24
TR5 (158)	74	76	8
TR6 (154)	64	88	2
TR7 (166)	58	104	4
TR8 (162)	54	94	14
TR9 (158)	60	88	10

Locations	Fragment	Film	Fiber
TR10 (172)	74	96	2
TR11 (138)	30	108	0
TR12 (46)	16	28	2
TR13 (104)	30	70	4
TR14 (90)	28	54	8
TR (1994)	**742**	**1102**	**150**
BaR1 (60)	26	32	2
BaR2 (120)	56	62	2
BaR3 (196)	70	106	20
BaR (376)	**152**	**200**	**24**
Total (4190)	**1574**	**2258**	**358**

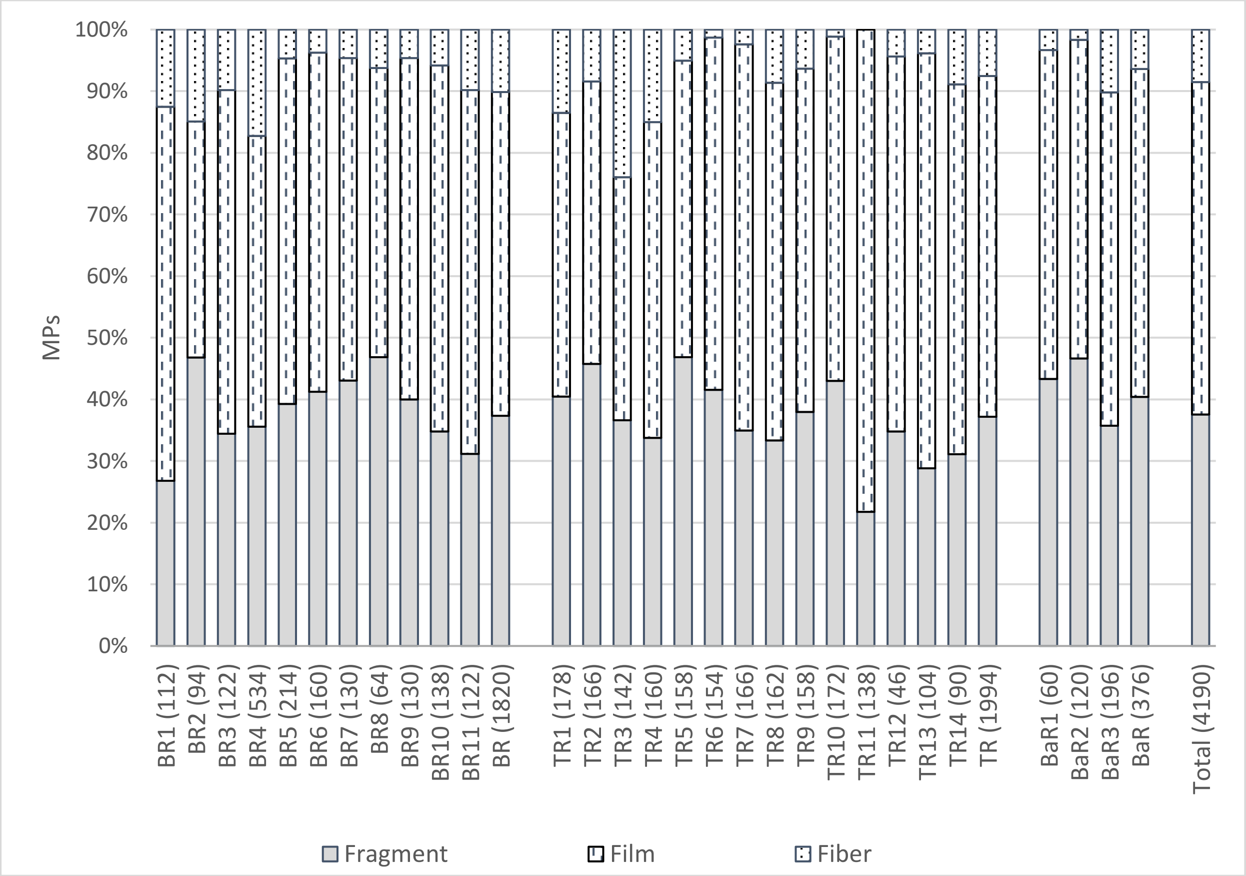


Figure 4.6: Shape-based distribution (%) of microplastics extracted from different sediment sampling points. The number in brackets corresponds to the number of microplastics found at each sampling site.

4.3.2 Sizes

All sediment samples were contaminated with different sizes of MPs. The extracted MP particles were classified into five size categories as follows: 0.1-0.3 mm, 0.3-0.5 mm, 0.5-1 mm, 1-2 mm and 2-5 mm. The highest proportions were found between 2 and 5 mm (51.84%) size category followed by 0.3-0.5 mm (15.23%), 1-2 mm (14.84%), 0.5-1 mm (12.89%), and 0.1-0.3 mm (5.20%) (Figure 4.7).

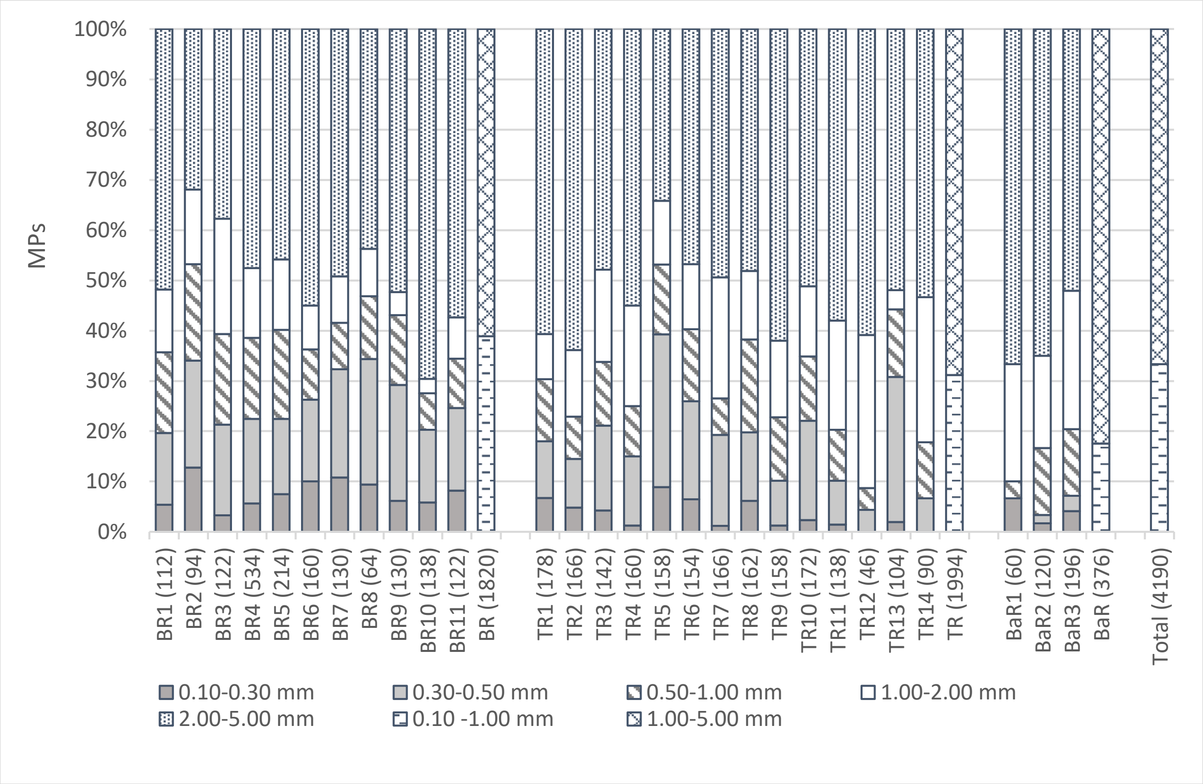


Figure 4.7: Size-based distribution (%) of microplastics extracted from different sediment sampling points. The number in brackets corresponds to the number of microplastics found at each sampling site.

However, the overall results were categorized into small microplastics (<1 mm) and large microplastics (1-5 mm) (Barrows et al., 2017; Eo et al., 2018; Frias et al., 2018). The results were found to contain larger-sized MPs (67%) than smaller-sized MPs (33%) of totally identified MPs. The major proportion of large MPs was found in previous studies (Islam et al., 2022; Mu et al., 2019; Zhang et al., 2020). The predominant large MPs revealed that the rapid formation of biofilm due to high nutrient levels in water and weak hydrodynamics may lead to their settlement before experiencing deep weathering (Zhang et al., 2017). However, large MPs can be traveled long distances and relatively remote locations can contaminate (Browne et al., 2010). Also, the large MPs convert to small MPs due to degradation and various environmental processes with time (Andrady, 2011b) and the smaller MPs particles would be more hazardous than larger particles (Lei et al., 2018). The shape-sized based characteristics revealed that the major proportion of fibers were small MPs in BR, whereas overall large MPs of all shapes (fragments, films and fibers) were dominated (Figure 4.8; Table C2). Table 4.4 shows the Number of various sized MPs in different sediment sampling points.

Table 4.4: Numbers of various sized MPs in different sediment sampling points.

Locations	**Size of MPs (mm)**				
	0.10-0.30	**0.30-0.50**	**0.50-1.00**	**1.00-2.00**	**2.00-5.00**
BR1 (112)	6	16	18	14	58
BR2 (94)	12	20	18	14	30
BR3 (122)	4	22	22	28	46
BR4 (534)	30	90	86	74	254
BR5 (214)	16	32	38	30	98
BR6 (160)	16	26	16	14	88
BR7 (130)	14	28	12	12	64
BR8 (64)	6	16	8	6	28
BR9 (130)	8	30	18	6	68
BR10 (138)	8	20	10	4	96
BR11 (122)	10	20	12	10	70
TR1 (178)	12	20	22	16	108
TR2 (166)	8	16	14	22	106
TR3 (142)	6	24	18	26	68
TR4 (160)	2	22	16	32	88
TR5 (158)	14	48	22	20	54
TR6 (154)	10	30	22	20	72
TR7 (166)	2	30	12	40	82
TR8 (162)	10	22	30	22	78
TR9 (158)	2	14	20	24	98
TR10 (172)	4	34	22	24	88
TR11 (138)	2	12	14	30	80
TR12 (46)	0	2	2	14	28
TR13 (104)	2	30	14	4	54
TR14 (90)	0	6	10	26	48
BaR1 (60)	4	0	2	14	40
BaR2 (120)	2	2	16	22	78
BaR3 (196)	8	6	26	54	102

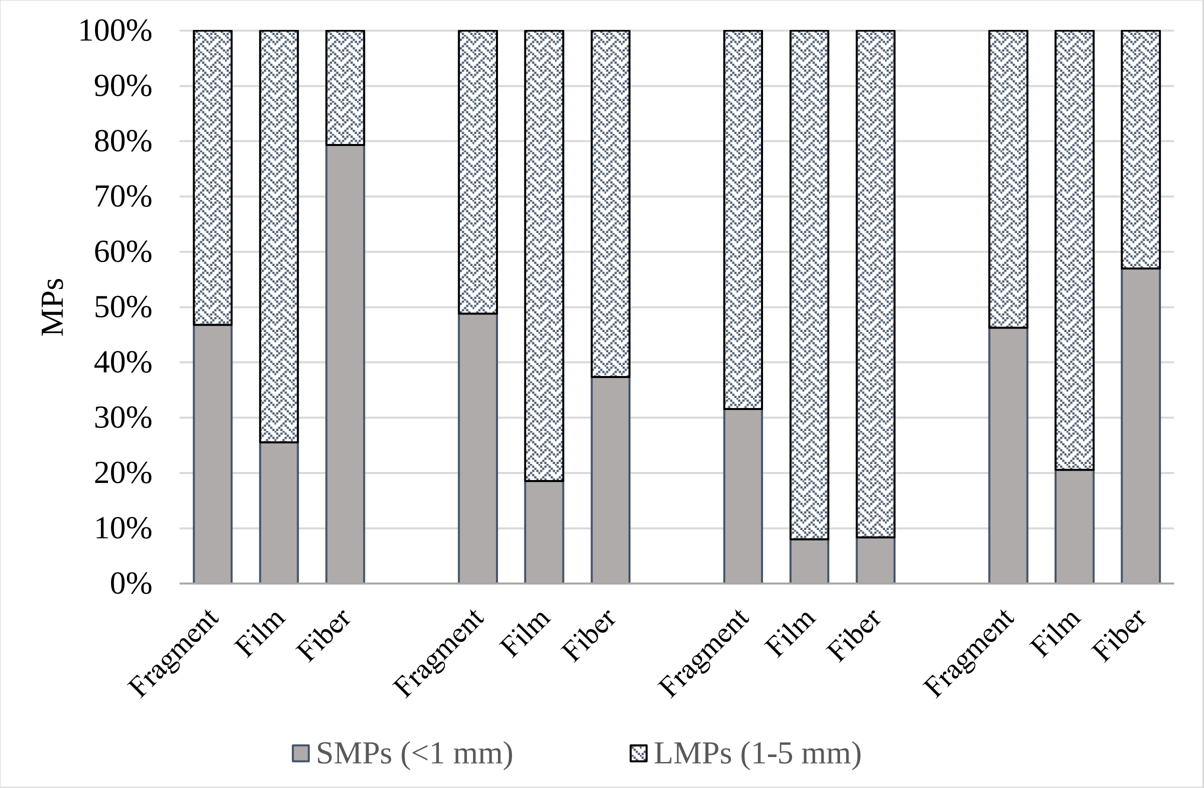


Figure 4.8: Shape-Size based proportion of MPs.

4.3.3 Colors

The extracted MPs were observed in various colors. The white (18.77%) MPs were major abundance followed by transparent (14.90%), yellow (14.37%), blue (14.37%), red (12.03%), green (11.27%), black (8.40%) and grey (5.87%) (Figure 4.9). The higher abundance of white and transparent colors indicated that MPs were weathered and faded due to light as well as affected by hydraulic action (Ren et al., 2020). Besides, the colorful MPs are largely generated from various color household plastic products such as jugs, bowls, baskets, bins, mugs, and baby care items used in Bangladesh. Most of these plastic industries are situated on the bank of the surrounding rivers of Dhaka city and their improper waste management may lead to generating colorful MPs. These colorful MPs seem like some natural food of sedimentary habitats and mistaken ingestion might happen by aquatic organisms (Kabir et al., 2020; Wright et al., 2013). So, the color variety of MPs might be harmful to aquatic organisms. The Number of various color MPs in different sediment sampling points is shown in Table 4.5.

Table 4.5: Numbers of various color MPs in different sediment sampling points.

Locations	Black	White	Grey	Yellow	Red	Green	Blue	Transparent
BR1 (112)	7	2	0	8	8	7	10	14
BR2 (94)	7	5	0	3	3	12	6	11
BR3 (122)	0	5	9	10	17	6	14	0
BR4 (534)	33	48	18	42	15	22	52	37
BR5 (214)	3	20	3	6	38	18	10	7
BR6 (160)	9	16	4	9	11	14	1	16
BR7 (130)	1	12	1	12	8	5	15	11
BR8 (64)	3	5	4	6	0	3	4	7
BR9 (130)	3	7	1	8	8	15	12	11
BR10 (138)	4	17	3	9	6	7	12	11
BR11 (122)	3	11	3	11	5	6	13	9
BR (1820)	**73**	**148**	**46**	**124**	**119**	**115**	**149**	**134**
TR1 (178)	5	27	6	11	6	2	18	14
TR2 (166)	4	22	3	13	7	8	14	12
TR3 (142)	9	11	6	9	15	6	8	7
TR4 (160)	8	16	6	9	11	12	9	10
TR5 (158)	9	5	12	20	10	5	10	8
TR6 (154)	14	15	7	9	6	8	7	11
TR7 (166)	8	16	3	13	8	2	15	18
TR8 (162)	6	9	3	21	11	12	8	11
TR9 (158)	2	26	3	6	9	6	15	12
TR10 (172)	8	23	6	13	9	5	6	16
TR11 (138)	5	28	6	10	3	4	5	8
TR12 (46)	1	5	2	0	3	6	5	1
TR13 (104)	6	9	2	10	3	5	4	13
TR14 (90)	9	6	4	8	2	2	3	11
TR (1994)	**94**	**218**	**69**	**152**	**103**	**83**	**127**	**152**
BaR1 (60)	0	6	0	2	4	9	6	3
BaR2 (120)	2	5	1	3	18	17	8	6
BaR3 (196)	7	16	7	20	8	12	11	17
BaR (376)	9	27	8	25	30	38	25	26
Total (4190)	**176**	**393**	**123**	**301**	**252**	**236**	**301**	**312**

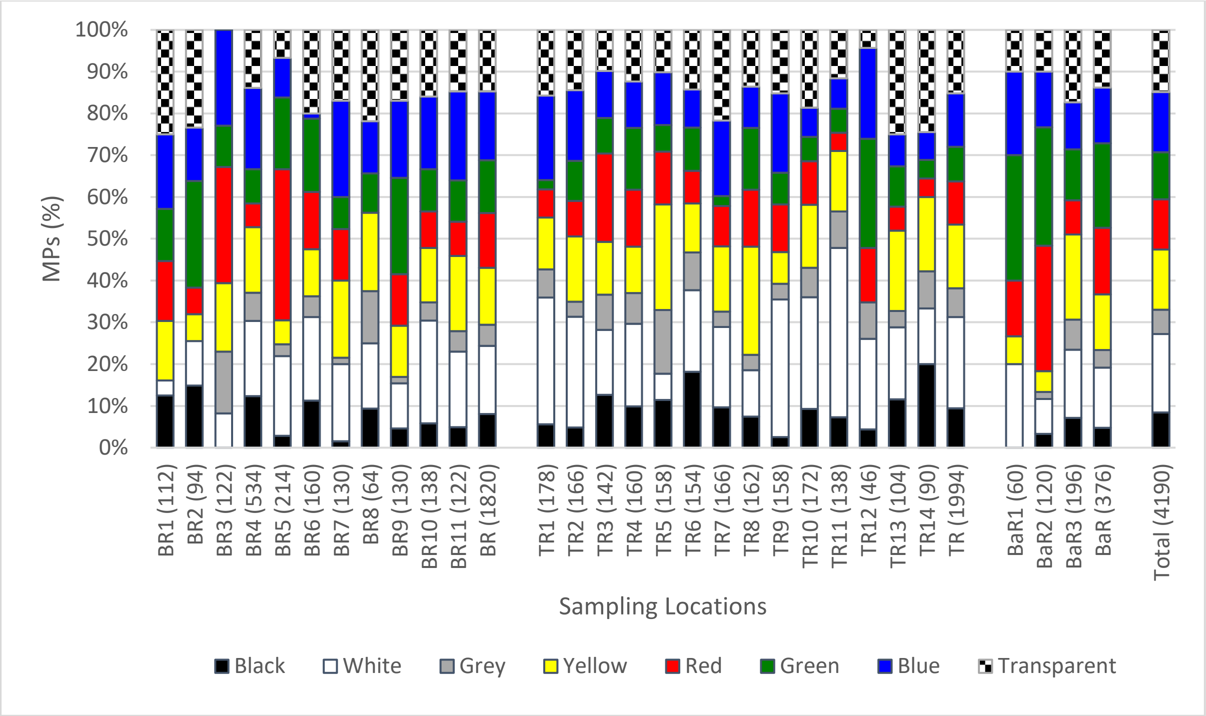


Figure 4.9: Color-based distribution (%) of microplastics extracted from different sediment sampling points. The number in brackets corresponds to the number of microplastics found at each sampling site.

4.3.4 Polymer types

Polymer types were identified through FTIR analysis (Table 4.6). Polyethylene (PE) (33.39%) was the highest proportion among eleven different types of identified polymers. The results revealed that polypropylene (PP) (27.30%), polyethylene terephthalate (PET) (17.04%), polyvinyl alcohol (PVA) (6.71%), polystyrene (PS) (6.32%), polyvinyl chloride (PVC) (5.06%), nylon 6 (2.22%), polyphenylene sulfide (PPS) (0.86%), polyurethane (PUR) (0.41%), epoxy resin (EP) (0.41%), acrylonitrile–butadiene–styrene (ABS) (0.29%) (Figure 4.10). PE and PP were dominant in this study due to mostly urban land use sources. This finding is similar to the previous studies suggesting that the urban land-use affected rivers posed a higher abundance of PE, and PP (Lin et al., 2018; Peng et al., 2018; J. Wang et al., 2017). Similarly, the higher abundance of PE and PP were found in previous study on MPs of Buriganga river (Islam et al., 2022). An analysis of European plastics production, demand, and waste data in 2021 reported that PE and PP were the most widely used polymers in 2019 and 2020 (Plastics Europe, 2021). The dominant PE, PP, and PET were commonly observed among the sampling locations. Also, all non-predominant polymers were found together with predominant polymers at the river port and industrial area affected sampling stations BR4 and TR6 respectively. Among the non-predominant polymers PUR was observed in all rivers but ABS, EP, and PPS were not observed in the Balu river. The PE and PP were observed as fragments, films, and fibers shapes; PVA, PVC, and ABS were found as fragments and films. PET was found as fragments and fibers. The observed shapes of MP polymers are provided in the Table 4.7.

Table 4.6: Numbers of various polymers identified in different sediment sampling points.

Locations	PP	PVA	PET	PE	PS	Nylon 6	PPS	EP	PVC	ABS	PUR
BR1 (112)	27	13	17	47	3	2	0	1	2	0	0
BR2 (94)	11	8	14	36	7	7	0		10	0	1
BR3 (122)	17	0	44	37	9	4	0	5	2	0	4
BR4 (534)	133	34	59	191	59	22	7	5	17	4	3
BR5 (214)	67	11	23	61	12	3	0	0	37	0	0
BR6 (160)	53	7	13	71	8	4	0	0	4	0	0
BR7 (130)	47	5	19	37	13	2	4	0	2	1	0
BR8 (64)	31	3	5	17	5	0	0	0	3	0	0
BR9 (130)	49	3	33	37	2	1	0	0	5	0	0
BR10 (138)	53	7	6	43	9	7	9	1	2	0	1
BR11 (122)	29	3	27	51	2	3	0	0	7	0	0
BR (1820)	**517**	**94**	**260**	**628**	**129**	**55**	**20**	**12**	**91**	**5**	**9**
TR1 (178)	37	13	39	43	21	4	3	0	17	0	1
TR2 (166)	49	11	31	39	19	3	0	0	14	0	0
TR3 (142)	46	9	36	35	9	2	3	0	2	0	0
TR4 (160)	39	4	41	61	4	0	2	0	5	1	3
TR5 (158)	35	8	37	59	7	3	0	0	9	0	0
TR6 (154)	31	12	23	57	3	7	4	3	10	2	2
TR7 (166)	67	17	12	54	13	1	0	0	2	0	0
TR8 (162)	37	19	33	53	2	0	3	0	14	1	0
TR9 (158)	43	12	23	59	9	2	1	0	9	0	0
TR10 (172)	49	13	36	37	19	3	0	1	11	3	0
TR11 (138)	31	13	29	48	7	1	0	1	7	0	1
TR12 (46)	9	3	7	22	3	0	0	0	2	0	0
TR13 (104)	22	4	17	53	6	1	0	0	1	0	0
TR14 (90)	33	1	2	36	4	2	0	0	12	0	0
TR (1994)	**528**	**139**	**366**	**656**	**126**	**29**	**16**	**5**	**115**	**7**	**7**
BaR1 (60)	11	2	3	33	5	4	0	0	2	0	0
BaR2 (120)	21	14	38	39	4	2	0	0	1	0	1
BaR3 (196)	67	32	47	43	1	3	0	0	3	0	0
BaR (376)	**99**	**48**	**88**	**115**	**10**	**9**	**0**	**0**	**6**	**0**	**1**
Total (4190)	**1144**	**281**	**714**	**1399**	**265**	**93**	**36**	**17**	**212**	**12**	**17**

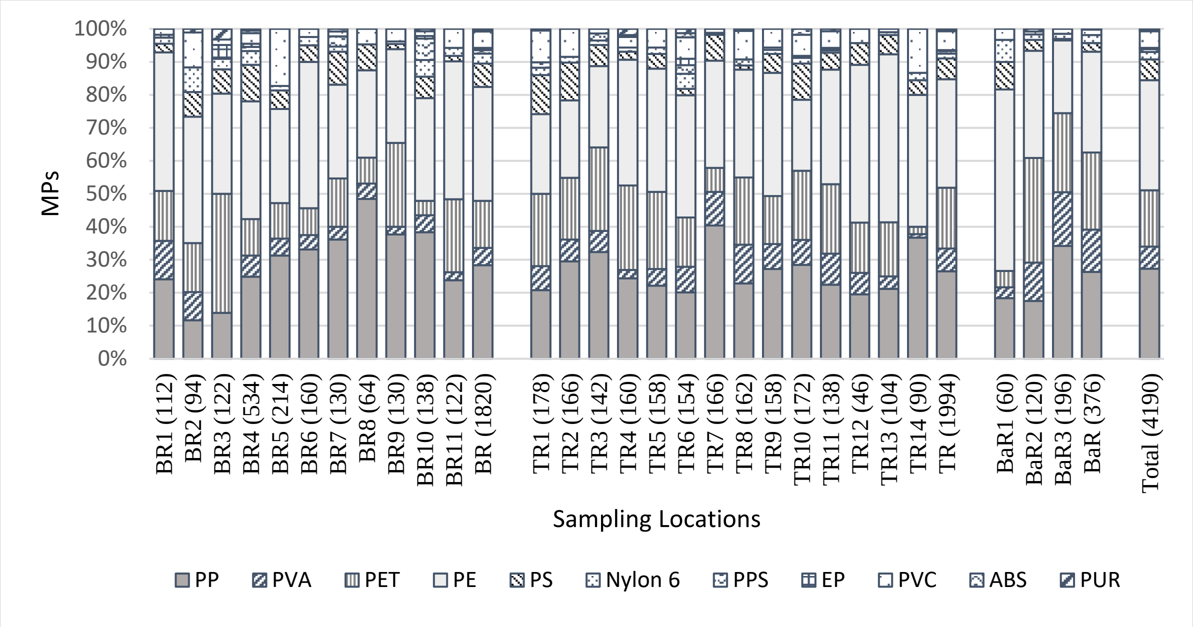


Figure 4.10: Polymer-based distribution (%) of microplastics extracted from different sediment sampling points. The number in brackets corresponds to the number of microplastics found at each sampling site.

Most of the polymers in sediment samples were higher density (>1 g/cm^3) except PE (0.91-0.97 g/cm^3) and PP (0.85-0.92 g/cm^3) (Jones et al., 2020; Morét-Ferguson et al., 2010). The polymers get settled down from the water to sediment due to relatively higher density than freshwater. However, the potential reason for the higher abundance of PE and PP in sediment samples was due to increased density by weathering and biofouling and subsequently settled down in sediments (Matsuguma et al., 2017; Rahman et al., 2020).

From the distribution point of view, PE, PP, and PET particles were detected at all the stations along the rivers. There was strong correlation were found for the PE (Spearman rank correlation, p value = 0.000 < 0.05; r^2 = 0.631) and PET (Spearman rank correlation, p value = 0.001 < 0.05; r^2 = 0.586) polymers with the among MP abundance (Figure 4.11 and Figure 4.12). Also, a significant strong correlation (Spearman rank correlation, p value = 0.000 < 0.05; r^2 = 0.810) was observed between MP abundances and PP polymers (Figure 4.13). However, the abundance of PE and PP was higher than PET, while the higher density of PET (1.38-1.41 g/cm^3) might be a potential marker polymer for MP pollution in river sediment due to their existence along all river stations in significant abundance.

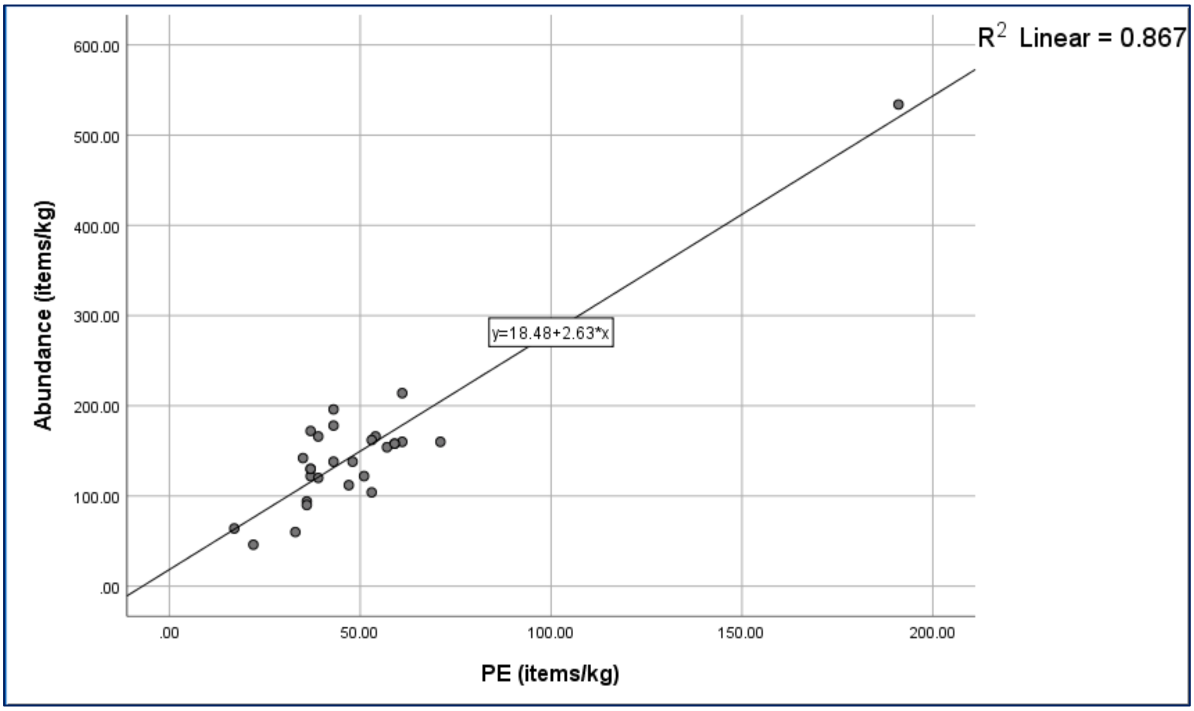


Figure 4.11: Correlation between PE and MPs abundance.

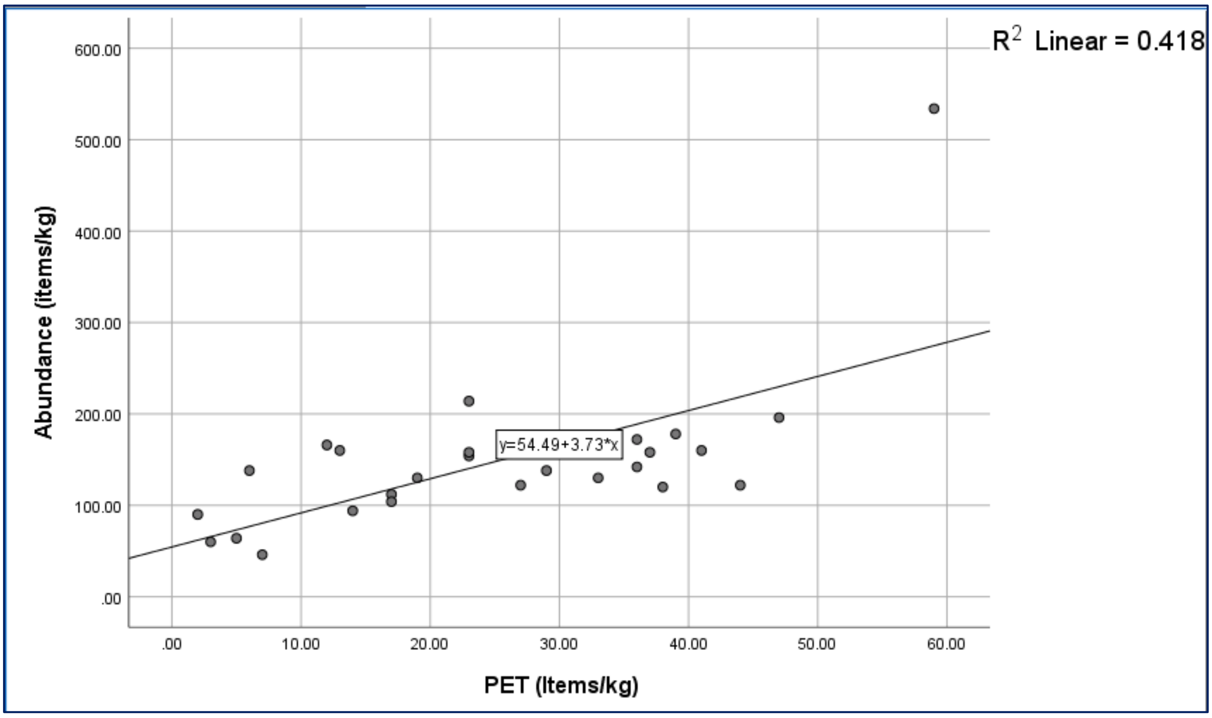


Figure 4.12: Correlation between PET and MPs abundance.

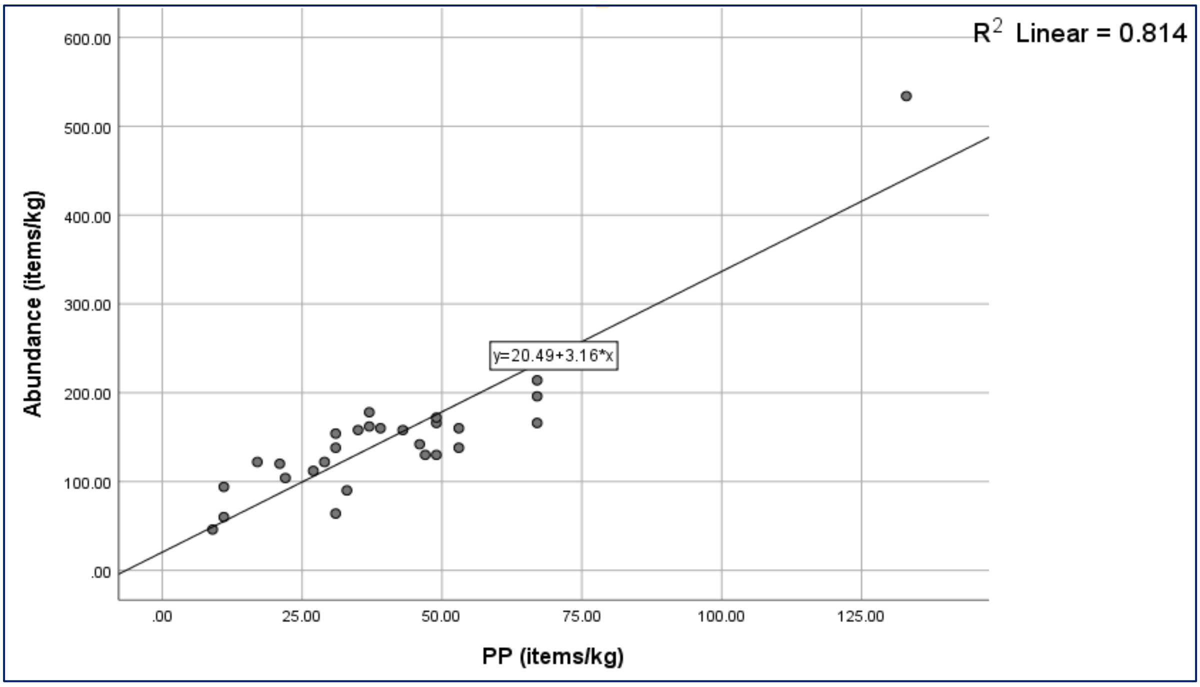


Figure 4.13: Correlation between PP and MPs abundance.

4.4 Potential sources and occurrences of MP

The predominant PE, PP, and PET were ubiquitous along the river stations. PE and PP were found as fragments, films, and fibers and they are commonly referred to as single-use plastics. They mainly originated from domestic, industrial, commercial, and agricultural sources and are commonly used for food packaging, straws, stirrers, bottles, pipes, containers, toys, etc. (Hossain et al., 2021; Plastics Europe, 2021).

PVA and PET have a widespread application in the textile and food packaging industry (Gaaz et al., 2015). These polymers were present among most of the sampling stations. PVC was present among all river stations due to its uses for the large-scale production of cable insulations, equipment parts, pipes, laminated materials, and fiber manufacture. The ubiquitous presence of PVC indicates that both urban and agricultural sources may release PVC polymer. Nylon 6 and PPS fibers were abundant in highly urban affected stations of the BR. The sewerage discharge, wastewater from domestic washing machines, WWTP, fishing gear, and urban sources might release Nylon 6 and PPS fibers (Browne et al., 2011; Conley et al., 2019; Horton and Dixon, 2018). Epoxy resin (EP) was mostly found in the industrial, residential, and commercial affected stations of the BR (BR3, BR4) and TR (TR6), which might be sourced from paints and coatings, structural adhesives, industrial tooling, aerospace industry, electronics industry and biomedical applications (Jin et al., 2015; Valášek et al., 2014).

Table 4.7 represents the density, applications, and observed shapes of Identified microplastics polymers. ABS were the lowest proportion among eleven identified polymers and were present in industrial and residential dominating stations of the BR (BR4, BR7) and TR (TR4, TR6, TR8, TR10). Also, their application in automotive body parts, helmets, dashboards, wheel covers, luggage, furniture, caps, telephone sets, camera, etc. suggested that urban and residential areas might release ABS into the rivers (Begum et al., 2020). Thus, the various land use sources may contribute to release of different polymer types of MPs in river systems.

Overall, the sewage, industrial and household effluent discharge points are connected to the peripheral river system of Dhaka city and they are major sources of MPs pollution. Also, several factors such as lower flow rate of river water, presence of markets, plastic industries, plastic recycling industries, river port are contributing higher MPs content in these rivers.

Table 4.7: Density, applications, and observed shapes of identified microplastics polymers.

Polymers	**Abbreviations**	**Density (gm/cm^3)**	**Applications**	**Observed Shapes**
Polypropylene	PP	0.85-0.92	Food packaging, sweet and snack wrappers, hinged caps, microwave containers, pipes, automotive parts, bank notes, etc. (Plastics Europe, 2021)	Fragments, Films, Fibers
Polyethylene	PE	0.91-0.97	Agricultural film, food packaging film, toys, milk bottles, shampoo bottles, pipes, houseware, floor tiles, shower curtains, bubble wrap, wire insulation and electric cables, rubbish bags, reusable bags, trays and containers, chemical and detergent bottles, buckets, plants pots, outdoor furniture. (Jones et al., 2020)	Fragments, Films, Fibers
Polyethylene terephthalate	PET	1.38-1.41	Bottles for water, soft drinks, juices, cleaners, textile fibers, etc. (Plastics Europe, 2021)	Fragments, Fibers
Polyvinyl alcohol	PVA	1.19-1.31	Textile, paper, and food packaging industry (Gaaz et al., 2015)	Fragments, Films
Polystyrene	PS	1.04-1.08	Food packaging (dairy, fishery), building insulation, electrical and electronic	Fragments

Polymers	Abbreviations	Density (gm/cm^3)	Applications	Observed Shapes
			equipment, inner liner for fridges, eyeglasses frames, etc. (Plastics Europe, 2021)	
Polyvinyl chloride	PVC	1.16-1.41	Window frames, profiles, floor and wall covering, pipes, cable insulation, garden hoses, inflatable pools, etc. (Plastics Europe, 2021.)	Fragments, Films
Nylon 6		1.15	Fabrics in textile industry, parachutes, flak vests, tires for vehicles, surgical suture, dresses, under garments, ties, tapestry(Castelvetro et al., 2021)	Fibers
Polyphenylene sulfide	PPS	1.34	**Electrical and Electronics (EandE)** Uses include electronic components including connectors, coil formers, bobbins, terminal blocks, relay components, moulded bulb sockets for electrical power station control panels, brush holders, motor housings, thermostat parts and switch components. **General Industries** Cooking appliances, sterilisable medical, dental and laboratory equipment, hair dryer grills and components.	Fibers
Polyurethane	PUR	1.01-1.21	Building insulation, pillows and mattresses, insulating foams for fridges, etc. (Plastics Europe, 2021)	Fragments
Epoxy resin	EP	1.14	Potting and encapsulating compounds, tooling compounds, molding powders, and adhesives (Jin et al., 2015; Valášek et al., 2014)	Fragments
Acrylonitrile–butadiene–styrene	ABS	1.0-1.05	Domestic appliances, telephone handsets computer and other office equipment housings, lawn mower covers, safety helmets, luggage shells, pipes and fitting, Medical devices, cosmetics,	Fragments, Films

Polymers	Abbreviations	Density (gm/cm^3)	Applications	Observed Shapes
			housewares, automobiles, business equipment, cabinets and casings, baths, shower trays, boat hulls and vehicle components, 3D printing (Begum et al., 2020)	

4.5 Comparison of worldwide MPs pollution in river sediment

The abundance and characteristics of MPs in these studied rivers were compared with previous study in Buriganga river sediment and other studies of river sediment around the world (Table 4.8). The abundance comparison revealed that MP abundances in this study were found similar magnitudes with the Ganga River of India, Brisbane River of Australia, Beishagang River of China, Lambourn River of UK, Antuã River, Portugal; higher magnitudes than earlier study in Buriganga river of Dhaka, Qin River of China, Ciwalengke River of Indonesia, Yongfeng River of China, Nanhuizui Tidal Flat of China; and lower magnitudes than Elbe River of Germany, West River of China, Cut River of UK, Amazon Rivers of Brazil, Tisza River of Central Europe. Furthermore, films, fragments, and fibers shape and PE, PP, PET, PVC, and PVA polymer were commonly observed in the river sediments around the world as well as in this study. However, SMPs (<1mm) were dominant in most of the river sediments around the world, while LMPs (>1mm) were dominant in this study which was similar to the earlier study in Buriganga river of Dhaka, Ayaragi River of Japan, Qin River of China, and Cut River of UK. Overall, a medium level of MPs pollution was found in the sediment of rivers around Dhaka city in comparison with various riverine environments worldwide.

Table 4.8: Summary of abundances and characteristics of microplastics in various riverine sediments reported worldwide.

Study Areas	Abundance (n/kg) (d.w.)	Concentration (mg/kg)	Predominant Characteristics				References
			Size (mm)	Shape	Color	Polymer	
Buriganga River, Bangladesh	$64 - 534^{r}$	$55.38 - 430.65^{r}$	1-5	Films, Fragments	Blue, White, Transparent	PE, PP, PET	This study
Turag River, Bangladesh	$46 - 178^{r}$	$13.56 - 203.23^{r}$	1-5	Films, Fragments	White, Transparent	PE, PP, PET	This study
Balu River, Bangladesh	$60 - 196^{r}$	$45.19 - 109.83^{r}$	1-5	Films, Fragments	Green, Red	PE, PP, PET	This study
Buriganga River, Bangladesh	$17.33 \pm 1.53 - 133.67 \pm 5.51^{r}$		1-3	Fragments	Transparent, Red, Blue	PP, PE	Islam et al., 2022
Ganga River, India	$107.57 - 409.86^{r}$		0.063-5	Fibers, Filaments		PE, PET	Sarkar et al., 2019
Brisbane River, Australia	$10 - 520^{r}$	$0.18 - 129.20^{r}$	<3	Films, Fragments, Fibers	White	PE, PA, PP	He et al., 2020
Huangpu River branch, China	72.3 ± 30.6^{m}		<0.1, 0.1-.05	Spheres	White	Rayon	Peng et al., 2018
Shajinggang River, China	76.5 ± 27.6^{m}		0.1–0.5	Spheres	White		Peng et al., 2018
Caohejing River, China	153.5 ± 77.1^{m}		<0.1, 0.1-.05	Spheres	White	PP	Peng et al., 2018
Beishagang River, China	160.0 ± 19.1^{m}		<0.1, 0.1-.05	Spheres	White	PE, Phenoxy Rasin	Peng et al., 2018
Jiangjiagang River, China	112.0 ± 5.6^{m}		0.1–0.5	Spheres	White	PP, Poly (Vinyl Stearate)	Peng et al., 2018
Yujiabang River, China	41.0 ± 12.7^{m}		<0.1, 0.1-.05	Spheres	White	PE	Peng et al., 2018

Study Areas	Abundance (n/kg) (d.w.)	Concentration (mg/kg)	Predominant Characteristics				References
			Size (mm)	Shape	Color	Polymer	
Nanhuizui Tidal Flat, China	5.3 ± 1.2^{m}		0.1-.05, 0.5-1	Fibers	Transparent, Red	PE, Rayon	Peng et al., 2018
Awano River, Japan	$16-212^{r}$	$3.54-44.74^{r}$	0.05–1	Fragments, Films	Transparent, White	PE, PP, PVA, PVC	Kabir et al., 2022
Ayaragi River, Japan	$24-608^{r}$	$3.94-282.45^{r}$	1–5	Fragments, Films	Transparent, White	PE, PP, PVA, PVC	Kabir et al., 2022
Asa River, Japan	$08-182^{r}$	$0.86-196.8^{r}$	1–5	Fragments, Films	Transparent, White	PE, PS, PVC	Kabir et al., 2022
Majime River, Japan	$14-1010^{r}$	$4.10-283.26^{r}$	1–5	Fragments, Films	Transparent, White	PVC, PET, PP	Kabir et al., 2022
Yongfeng River, China	$05-72^{r}$, 26 ± 23^{m}	$0.5-16.75^{r}$, 5.17 ± 5.65^{m}	<1	Films	Green	PP, PE	Rao et al., 2020
Daliao River, China	$100-467^{r}$, 237 ± 129^{m}			Films, Fragments		PE, EPR, PP	Xu et al., 2020
Shuangtaizi River, China	$133-300^{r}$, 170 ± 96^{m}			Films, Fragments, Fibers		PE, EPR, SBS	Xu et al., 2020
Leach River, UK	185 ± 42^{m}		1-2	Fibers		PET, PP, Polyarylsulphone	Horton et al., 2017
Lambourn River, UK	221 ± 95^{m}		1-2	Fibers		PET, PP, Polyarylsulphone	Horton et al., 2017
Cut River, UK	660 ± 77^{m}, 332 ± 161^{m}		1-2	Fragments, Fibers		PET, PP, Polyarylsulphone	Horton et al., 2017
Qin River, China	$0-97^{r}$		1-5	Sheets, Fibers	White, Blue	PP, PET, PE	Zhang et al., 2020
Amazon Rivers, Brazil	$417-8178^{r}$		0-1, 1-2		White/ Crystal		Gerolin et al., 2020

Study Areas	Abundance (n/kg) (d.w.)	Concentration (mg/kg)	Predominant Characteristics				References
			Size (mm)	Shape	Color	Polymer	
Maozhou River, Hong Kong Macao	$25 \pm 5\ to\ ^{r}$ 360 ± 90		0.1-1	Fragments	Transparent, White	PE, PP, PS, PVC	Wu et al., 2020
Antuã River, Portugal	$18 - 629^{r}$	$2.6 - 71.7^{r}$		Fragments, Fibers	Colored	PP, PE	Rodrigues et al., 2018
Atoyac River Basin, Mexico	$33.33 - 400^{r}$			Films, Fragments	Colored, White		Shruti, 2019
Elbe River, Germany	2080 ± 4670^{m}		<0.416	Spheres, Fragments	Transparent, Blue, White	PE, PS, PP	Scherer et al., 2020
Yushan River, China	$30 - 70^{r}$, 44 ± 18^{m}	$3.5 - 53^{r}$, 30.5 ± 23^{m}	0.2-0.5, 0.5-1, 1–1.5	Films, Fibers	Transparent		Niu et al., 2021
St. Lawrence River, North America	$65 - 7562^{r}$, 832 ± 150^{m}		<0.4	Microbeads, Fragments, Fibers			Crew et al., 2020
West River, China	$2560 - 10240\ ^{r}$		<0.5	Fibers		PP, PE	Huang et al., 2021
Tisza River, Central Europe	3177 ± 1970^{m}			Fibers			Kiss et al., 2021
Ciwalengke River, Indonesia	30.3 ± 15.9^{m}		0.5-1, 1-2	Fibers		PES	Alam et al., 2019
Rhine River, Germany	260 ± 10 to ^{r} 11070 ± 600		0.011-0.5			APV	Mani et al., 2019

r- indicates range (minimum to maximum)

m- indicates mean

4.6 Ecological Risks Assessment of MPs pollution

4.6.1 Pollution load Index (PLI)

The PLI results indicated that all sampling locations were polluted by MPs since PLI value was greater than one, which was considered polluted (Tomlinson et al., 1980) (Table 4.10). All sampling sites had PLI>1 whereas the minimum MPs abundance (C_0=46 n/kg) found in this study was considered as baseline abundance and the MPs abundance of other sites was higher than baseline abundance. A similar level of pollution was observed at most of the sampling sites except BR4, which had significantly higher MPs abundance and PLI than other sites. This is because the PLI value is directly related to the MPs abundance and the higher MPs abundance resulted in a greater pollution load index. However, ecological risks are not only dependent on abundance but also associated with polymeric hazards (Kabir et al., 2022). Therefore, the polymeric hazard index (PHI), and the ecological risk index (ERI) were also assessed for a clear understanding about ecological risks of MPs pollution in river sediment. The PHI, ERI, and associated risk category according to Hakanson, 1980; Kabir et al., 2022; Lithner et al., 2011, which were used for this study are shown in Table 4.9. Figure 4.14 represents the abundances and pollution load index (PLI) of microplastics (MPs) in different sediment sampling points. Hazard score and hazard statement of identified MP polymers are shown in Table C.1.

Table 4.9: Risk categories engaged in the MPs polymeric hazard index (PHI) and ecological risk index (ERI) (Hakanson, 1980; Kabir et al., 2022; Lithner et al., 2011).

PHI	ERI	Risk Category
<10	<150	Low
10-100	150-300	Low-medium
101-1,000	300-600	Medium
1,001-10,000	600-1,200	High
>10,000	>1,200	Very high

Table 4.10: PLI and abundance of MPs in different sediment sampling points.

Sampling Locations	Abundance (n/kg)	PLI
BR1	112	2.43
BR2	94	2.04
BR3	122	2.65
BR4	534	11.61
BR5	214	4.65
BR6	160	3.48

Sampling Locations	Abundance (n/kg)	PLI
BR7	130	2.83
BR8	64	1.39
BR9	130	2.83
BR10	138	3.00
BR11	122	2.65
BR	**165.45**	**3.06**
TR1	178	3.87
TR2	166	3.61
TR3	142	3.09
TR4	160	3.48
TR5	158	3.43
TR6	154	3.35
TR7	166	3.61
TR8	162	3.52
TR9	158	3.43
TR10	172	3.74
TR11	138	3.00
TR12	46	1.00
TR13	104	2.26
TR14	90	1.96
TR	**142.43**	**2.95**
BaR1	60	1.30
BaR2	120	2.61
BaR3	196	4.26
BaR	**125.33**	**2.44**

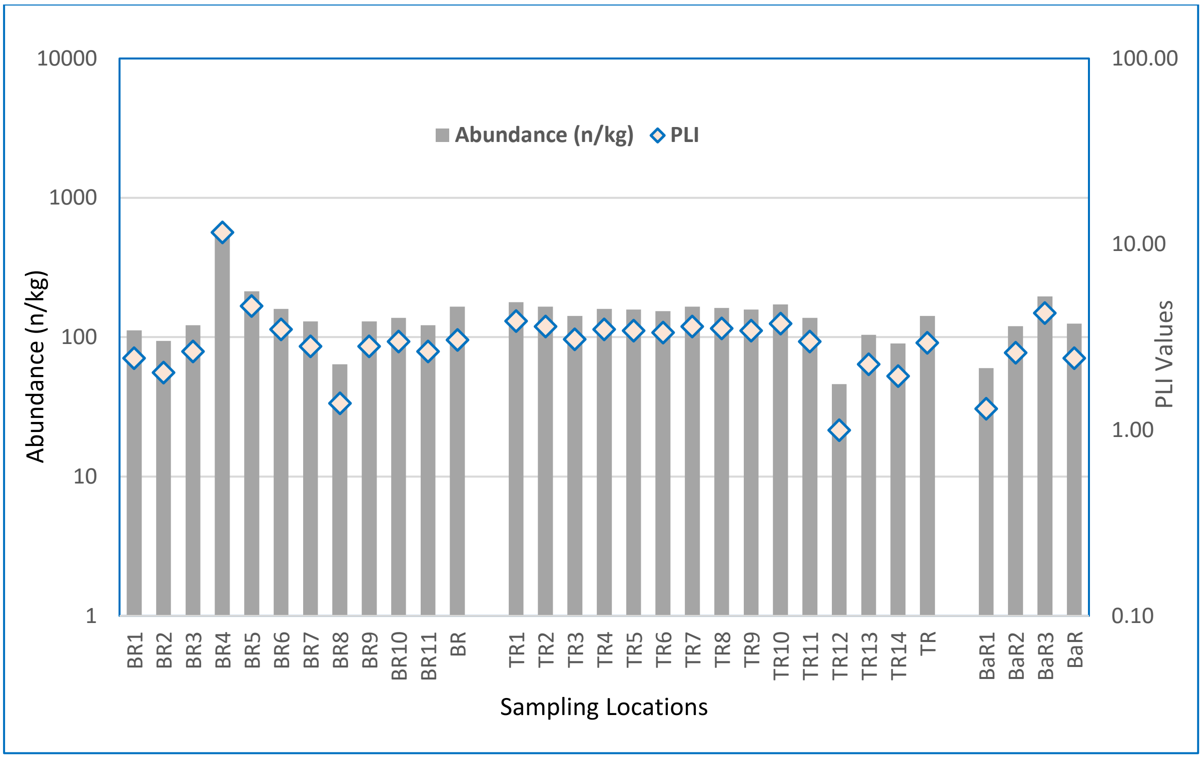


Figure 4.14: Abundances and pollution load index (PLI) of microplastics (MPs) in different sediment sampling points.

4.6.2 Polymeric Hazard Index (PHI)

BR, TR, and BaR were found to have a medium level of polymeric hazards according to the risk category. The PHI values were found to vary among the sampling sites based on the various MP polymers found in different river stations (Figure 4.18). However, most of the sampling sites observed medium-level polymeric hazards, except for greenfield-dominated stations (TR3, TR7, TR13) of TR, which exhibited low-medium hazard levels. Even though urban and industrial influenced sampling station BaR3 of BaR exhibited low-medium polymeric hazard since the station was affected by the less toxic polymer (PP) with the highest proportion and the polymeric hazard levels are the result of the proportion of found MP polymers and their hazard score (Kabir et al., 2022). Thus, PHI mainly depends on the presence of toxic polymers and their proportion.

The MP abundance was not considered to assess the PHI. For instance, TR12 revealed lower MPs abundance but higher PHI compared to BaR3. Similarly, Spearman rank correlation (p-value = 0.355 > 0.05; r^2 = 0.182) showed weak relationship between PHI and MP abundances (Figure 4.15). So, only polymeric hazard doesn't reveal ecological risk. Rather, ecological risks assessment depends on both MPs abundance and polymeric hazard index. Likewise, statistically significant correlations were found between the ERI and MP abundance (Spearman rank correlation, p-value = 0.002 < 0.05; $r^2 = 0.553$) (Figure 4.16); and ERI and PHI (Spearman rank correlation, p-value = 0.000 < 0.05; $r^2 = 0.878$) (Figure 4.17). Therefore, increased ERI were dependent on high MP abundance and PHI as well as presence of toxic polymers.

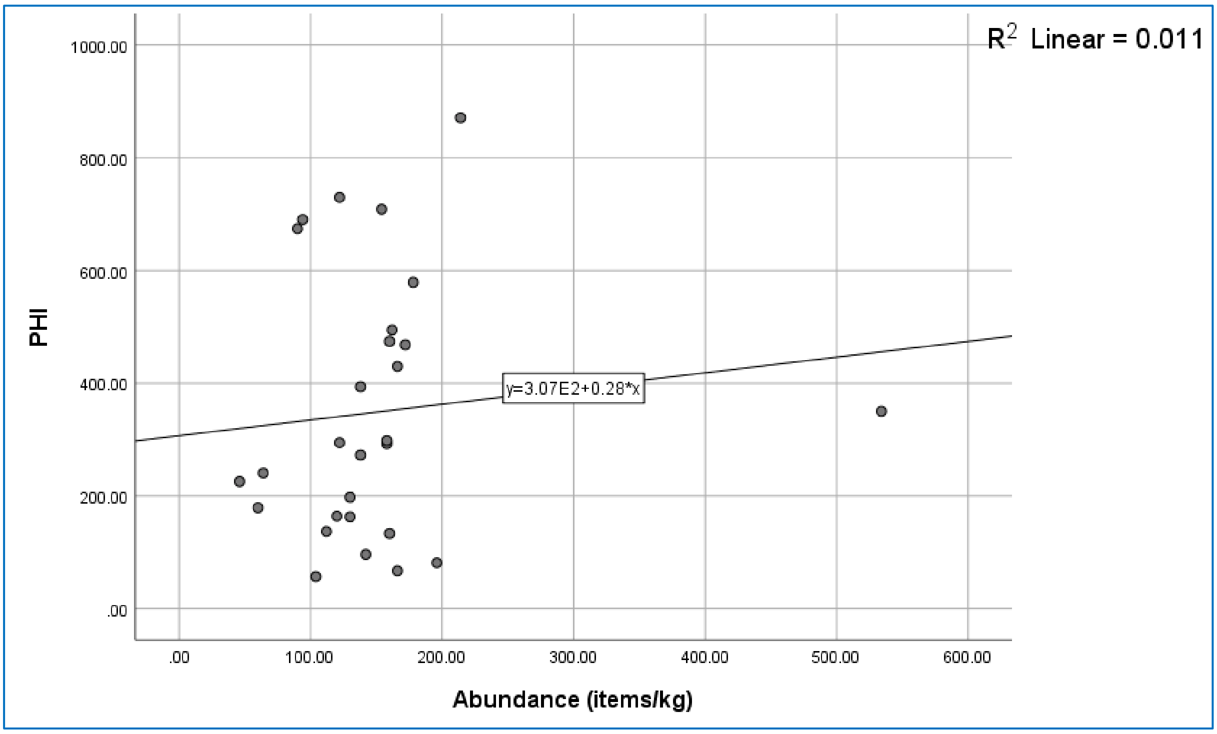


Figure 4.15: Correlation between MPs abundance and PHI.

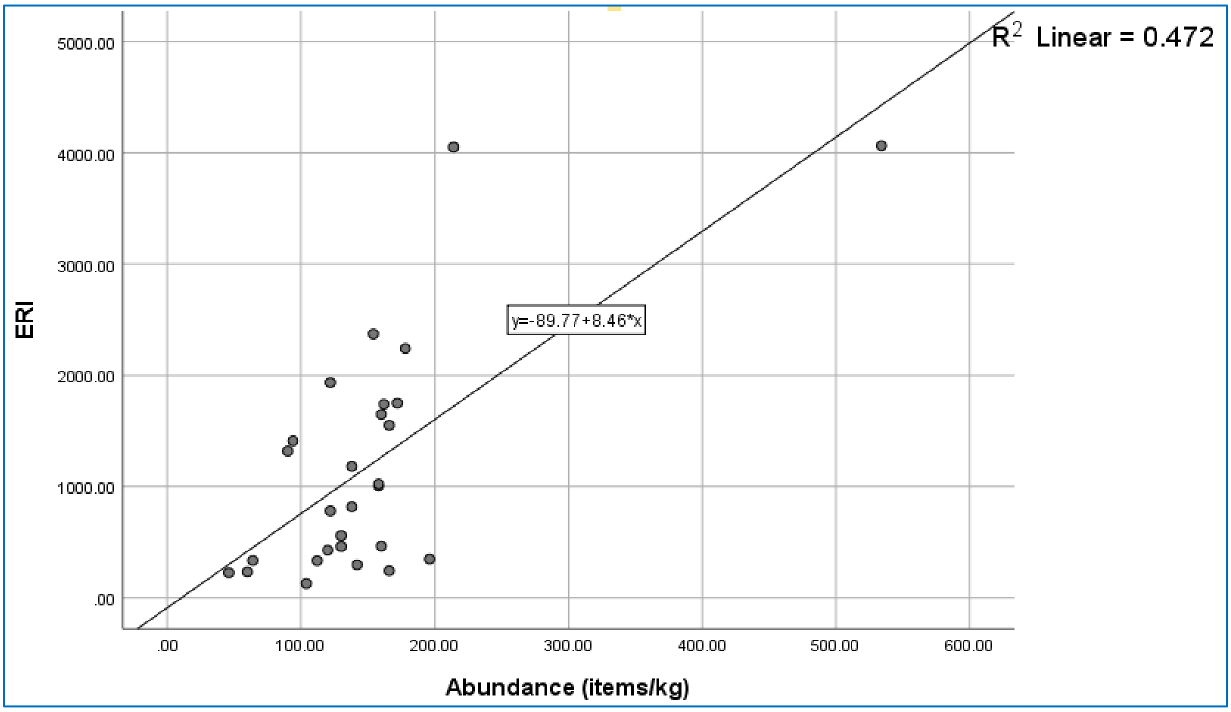


Figure 4.16: Correlation between MPs abundance and ERI.

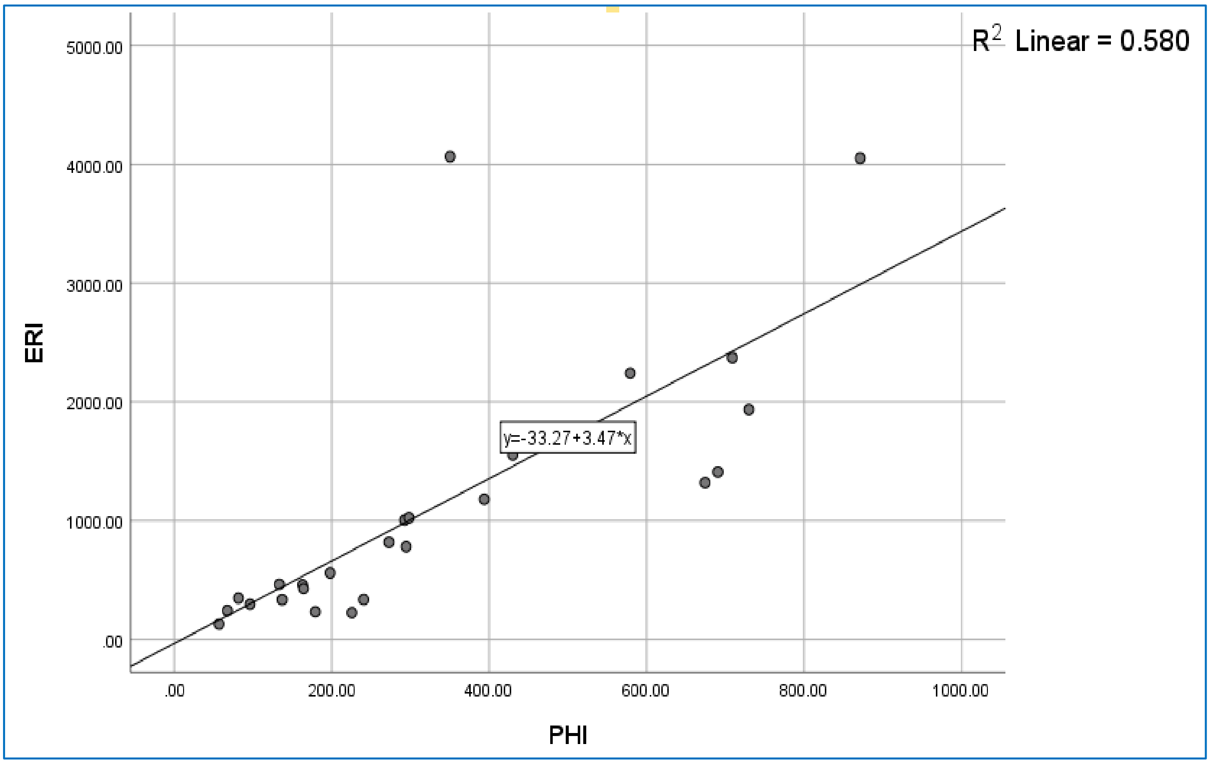


Figure 4.17: Correlation between PHI and ERI.

4.6.3 Ecological Risk Index (ERI)

The ecological risk index (ERI) value suggested low-medium to very high ecological risk among the sampling stations of rivers. Considering land use, we found that commercial and industrial land use dominating stations (BR2-BR5) of BR posed high risk. For the TR, the residential, industrial and commercial influenced stations (TR1, TR2, TR4, TR6, TR8, TR10 and TR14) of TR exhibited ecologically high risk. On the other hand, agricultural and greenfield dominating stations (TR3, TR7 and TR12) of TR revealed low-medium ecological risk. Similarly, low level ecological risk was observed in the greenfield influenced station TR13 of TR. All BaR stations were found to pose low-medium to medium risks (Table 4.11). Figure 4.18 represents the abundances, polymeric hazard index (PHI), and ecological risk index (ERI) of microplastics (MPs) in different sediment sampling points.

The findings suggested that the urban, industrial, and commercial sources can cause high ecological risk due to the widespread use of plastic, which contain highly toxic polymers. The ecological risk levels with land uses are illustrated in Figure 4.19. The identified pollution hotspots may be useful for further periodic monitoring and management as required by legislative authorities to reduce MP pollution.

Table 4.11: Ecological risk level of MPs in different sediment sampling points.

Sampling Locations	Abundance (n/kg)	PLI	ERI	PHI	Risk (ERI)	Risk (PHI)
BR1	112	2.43	333.30	136.89	Medium	Medium
BR2	94	2.04	1410.54	690.27	Very High	Medium
BR3	122	2.65	1935.28	729.70	Very High	Medium
BR4	534	11.61	4064.89	350.16	Very High	Medium
BR5	214	4.65	4051.91	870.97	Very High	Medium
BR6	160	3.48	463.85	133.36	Medium	Medium
BR7	130	2.83	460.15	162.82	Medium	Medium
BR8	64	1.39	334.65	240.53	Medium	Medium
BR9	130	2.83	558.83	197.74	Medium	Medium
BR10	138	3.00	817.63	272.54	High	Medium
BR11	122	2.65	780.83	294.41	High	Medium
BR	**165.45**	**3.06**	**916.21**	**299.55**	**High**	**Medium**
TR1	178	3.87	2240.46	578.99	Very High	Medium
TR2	166	3.61	1551.02	429.80	Very High	Medium
TR3	142	3.09	296.67	96.11	Low-Medium	Low-Medium
TR4	160	3.48	1649.59	474.26	Very High	Medium
TR5	158	3.43	1004.54	292.46	High	Medium
TR6	154	3.35	2372.54	708.68	Very High	Medium
TR7	166	3.61	242.78	67.28	Low-Medium	Low-Medium
TR8	162	3.52	1741.04	494.37	Very High	Medium
TR9	158	3.43	1023.30	297.92	High	Medium
TR10	172	3.74	1750.33	468.11	Very High	Medium
TR11	138	3.00	1180.74	393.58	High	Medium
TR12	46	1.00	225.52	225.52	Low-Medium	Medium
TR13	104	2.26	128.43	56.81	Low	Low-Medium
TR14	90	1.96	1318.91	674.11	Very High	Medium
TR	**142.43**	**2.95**	**868.27**	**294.59**	**High**	**Medium**
BaR1	60	1.30	233.48	179.00	Low-Medium	Medium
BaR2	120	2.61	427.85	164.01	Medium	Medium
BaR3	196	4.26	346.59	81.34	Medium	Low-Medium
BaR	**125.33**	**2.44**	**325.92**	**133.66**	**Medium**	**Medium**

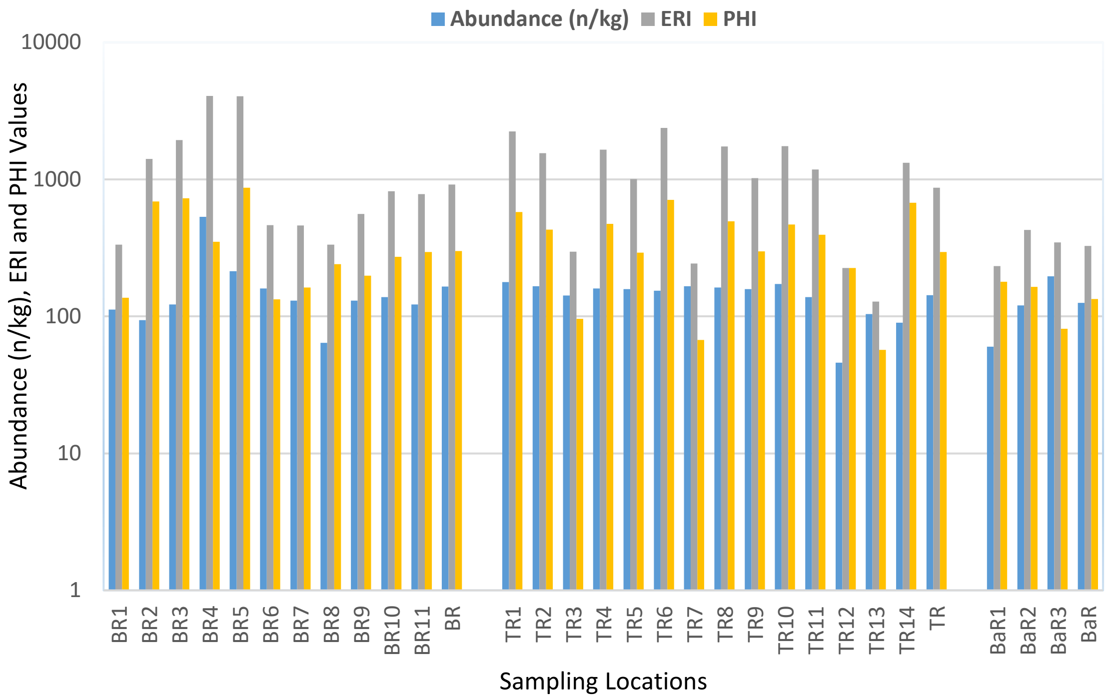


Figure 4.18: Abundances, polymeric hazard index (PHI), and ecological risk index (ERI) of microplastics (MPs) in different sediment sampling points.

4.7 Oxidation and weathering of MP particles

MP oxidation can be identified preliminary from the FTIR spectrum (Figure A1) (Laju et al., 2022; Rodrigues et al., 2018). The introduction of oxygen and the formation of carbonyl (CO) functional groups were observed into the different types of identified polymer spectra (Figure A.*2*). Therefore, these polymers are susceptible for photo-oxidation and chemical weathering due to the presence of carbonyl (CO) groups (Prata et al., 2020). Scanning electron microscopy (SEM) analysis of a few representative samples was employed to examine the surface morphological characteristics to confirm the perception of weathering undergone by the MPs (Zbyszewski and Corcoran, 2011).

SEM images revealed that the PE, PP, and PET polymers with the carbonyl group had linear fractures, cracks, pits, grooves, granules, and flakes and along with some crystalline formation (Figure 4.20). However, the same types of particles without carbonyl group had experienced relatively stable surfaces but still contained rough and irregular textures. This textural analysis suggested that MP particles in riverine sediment were weathered by various processes.

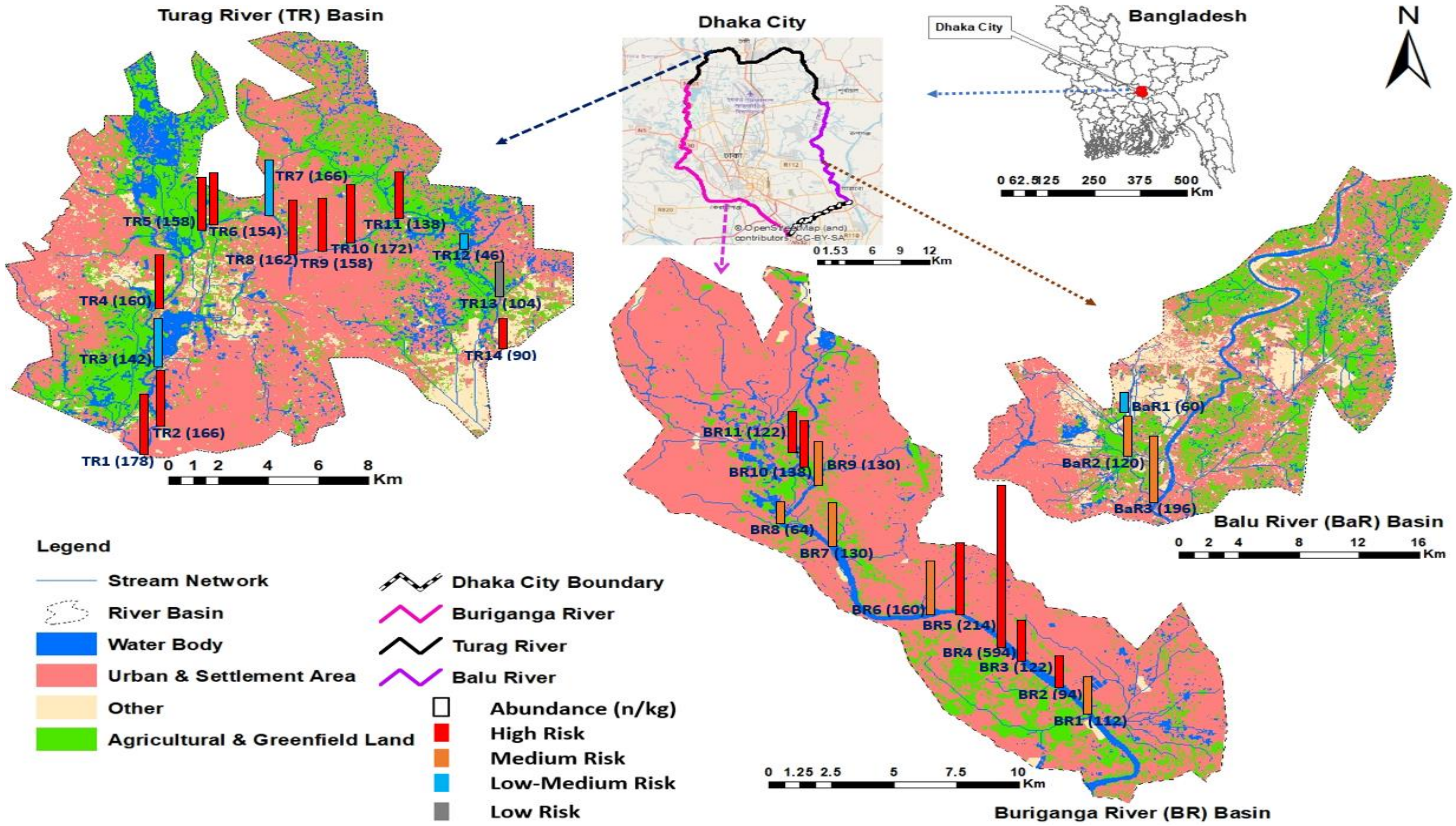


Figure 4.19: Land uses distributions, microplastics abundances and ecological risk levels among sampling stations in the three rivers around Dhaka city. (Column height level represents the microplastics abundance)

This weathering of MPs increases their adsorption performance towards the heavy metals, organic pollutants and microorganisms due to their surface changes and presence of oxygen containing functional groups (Laju et al., 2022; Liu et al., 2021; Luo et al., 2022). Several scientific investigations suggested that the surrounding rivers of Dhaka city are highly contaminated by heavy metal due to the presence of tanneries including other industries (Akbor et al., 2020; Al-Mizan et al., 2020; Hossain et al., 2021). Hence, there is a high absorption possibility of heavy metals by MPs due to presence of fractures, cracks, pits, grooves, and flakes in their surface (Luo et al., 2022). So, further detailed investigations of MPs weathering behaviors and metal contamination are recommended since these also play a vital role in toxicity to the ecosystem with their level of concentration and characteristics.

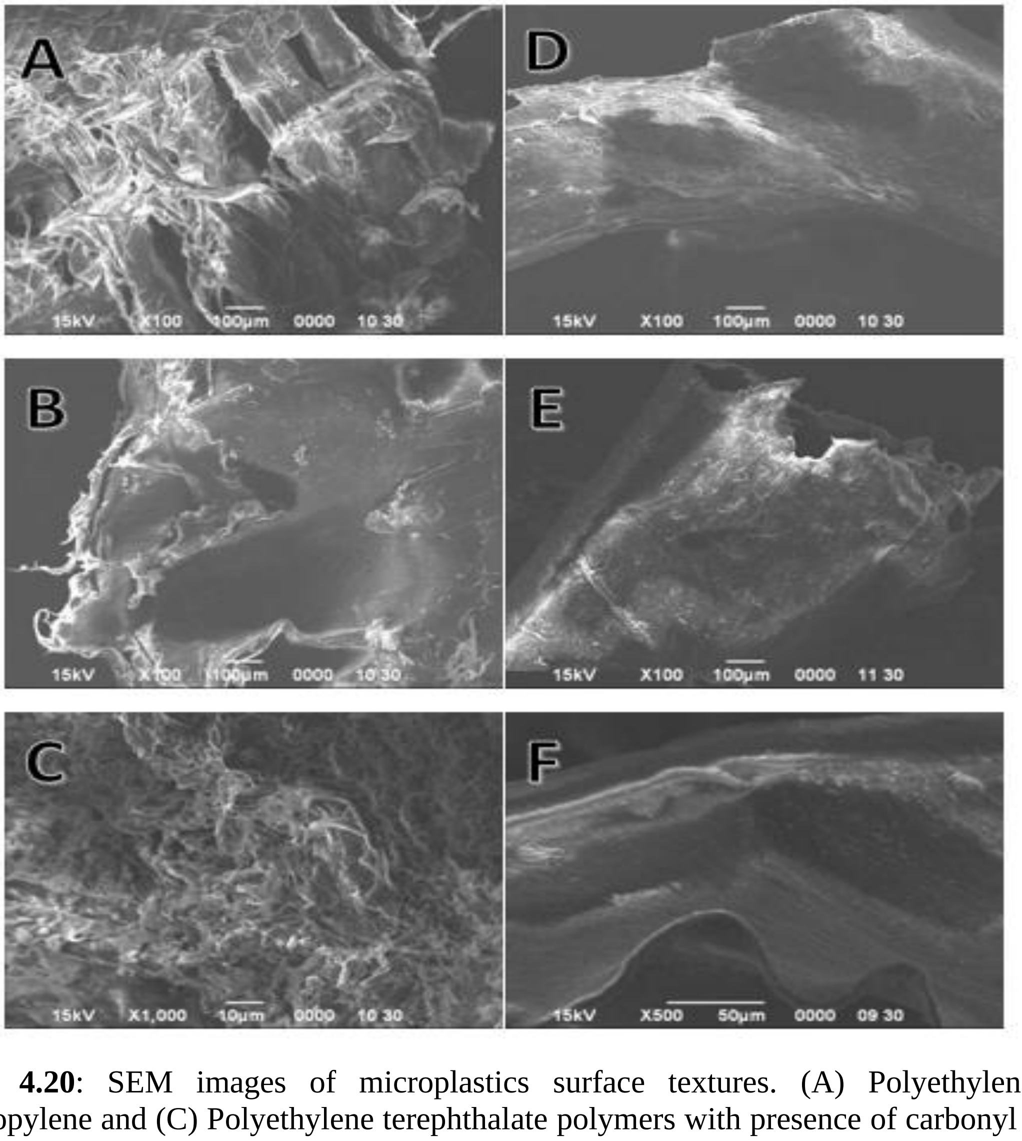


Figure 4.20: SEM images of microplastics surface textures. (A) Polyethylene, (B) Polypropylene and (C) Polyethylene terephthalate polymers with presence of carbonyl group; (D) Polyethylene, (E) Polypropylene and (F) Polyethylene terephthalate polymers in absence of carbonyl group.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

To date, little is known about the occurrence of MPs in the aquatic system of Bangladesh. Even all of the existing research articles focused on marine or beach samples (Banik et al., 2022; Rahman et al., 2020). Therefore, this study is the first comprehensive investigation of river sediment of the peripheral urban river systems, which assessed the ecological risk due to MPs pollution of Dhaka city. In this study, baseline information on the abundance, characteristics, and spatial distribution of microplastics in the sediment of Buriganga, Turag, and Balu rivers were investigated and the probable land use sources were identified and understood their influence on MPs pollution. Another major aim of this study was ecological risk assessment of MP through multiple indices. As a part of the study oxidation and weathering effect of MPs were observed. This Chapter presents the major conclusions from the study; it also presents the limitations of the study and recommendation for future studies.

5.2 Conclusions

This study had two objectives and the major findings of them are summarized below:

i) Abundance and characteristics of microplastic

- MPs were found in all sediment samples collected from sampling sites along the Buriganga, Turag, and Balu rivers. The abundance of MPs varies from 46 to 534 number particles per kilogram (kg) of dry sediment. The total number of MPs was 4190 particles among 28 sampling locations. The overall average and median MP abundance were 149.64 ± 83.70 n/kg and 140 n/kg. The mass concentration of MP varies from 13.56 mg/kg to 430.65 mg/kg with an overall average value 106.52 ± 73.17 mg/kg.

- The riverine sediments were predominated by film-shaped (53.89%), white-colored (18.77%), and larger-sized (1–5 mm) MPs. Most of the identified MP polymers were high density (>1 g/cm^3), which facilitated deposition to river sediment. Polyethylene (PE) (33.39%) was the most abundant among the observed polymer types.

ii) Ecological risks of microplastics

- The PLI results indicated that all sampling locations were polluted by MPs since PLI value was greater than one, which was considered polluted. The PHI values were found to vary among the sampling sites based on the various MP polymers found in different river stations. However, most of the sampling sites observed medium-level (101-1000) polymeric hazards.

- The average ecological risk index (ERI) value suggested that both BR and TR have high (1,200) ecological risk and BaR has medium (150-300) ecological risk. Ecological risk indices revealed that all the sampling sites were polluted with MPs and posed low-medium to very high-level risks to the ecosystems. In some sampling locations of both BR and TR, ERI value more than 1200 was observed, indicating very high ecological risk to those sampling locations. This very high ecological risk indicates the presence of high toxic polymers (PUR, ABS, PVC, EP and PPS) with higher abundance within the sampling stations.

- SEM images of MPs revealed that the polymers had linear fractures, cracks, pits, grooves, granules, and flakes and along with some crystalline formation. This textural analysis suggested that MP particles in riverine sediment were weathered, which are likely to cause toxic effects on ecosystems.

5.3 Limitations of the Study

i. The influences of population density on MPs abundance could not be identified due to unavailability of e-Stat population vector data in Bangladesh for each square of mesh.

ii. Baseline concentration is required to calculate pollution load index. However, due to lack of available background data in similar environments, the lowest MPs abundance obtained in this study was taken as the baseline concentration. This limitation will be overcome for further studies since this study will set a baseline data for the abundance, characteristics, and spatial distribution of microplastics in the river bed sediments around Dhaka city.

iii. In this study, efforts were made to observe oxidation and weathering of a few suspected MP samples using Scanning electron microscopy (SEM). SEM images revealed that weathering undergone by the MPs and the weathered MPs may absorb and carry metal elements. Unfortunately, no suitable laboratory in Bangladesh could be agreed/managed to conduct SEM-EDX analysis for comprehensive investigation on weathering and metal contamination of MP particles. Therefore, it was not possible to identify metal contaminant of microplastics in this study.

5.4 Recommendations for Future Research

The following recommendations can be made for future research in this field:

i. Efforts should be made to collect water samples (for analysis of microplastics) from the rivers around Dhaka city.

ii. Effect of seasonal variation on MPs abundances, concentrations and characteristics can also be identified in the river bed sediment around Dhaka city.

iii. Detailed investigations of MPs weathering behaviors and metal contamination are recommended since these also play a vital role in toxicity to the ecosystem with their level of concentration and characteristics.

iv. Further studies should be carried out to identify the impacts of MPs pollution on aquatic systems, habitats, and eventually on human health.

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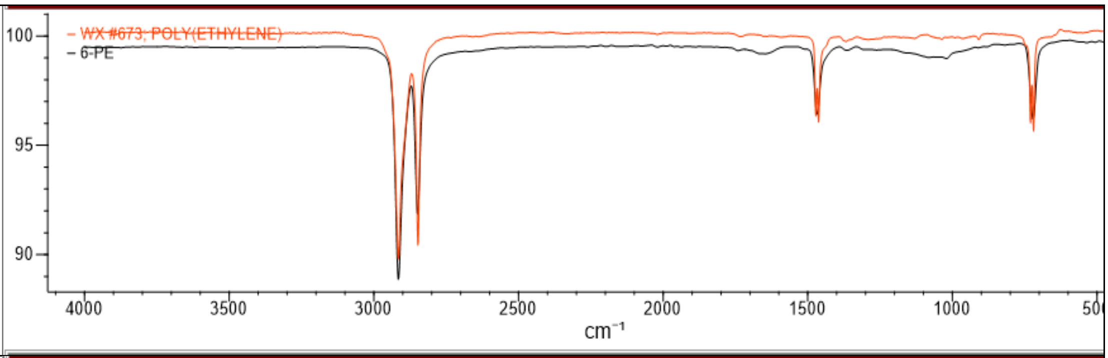
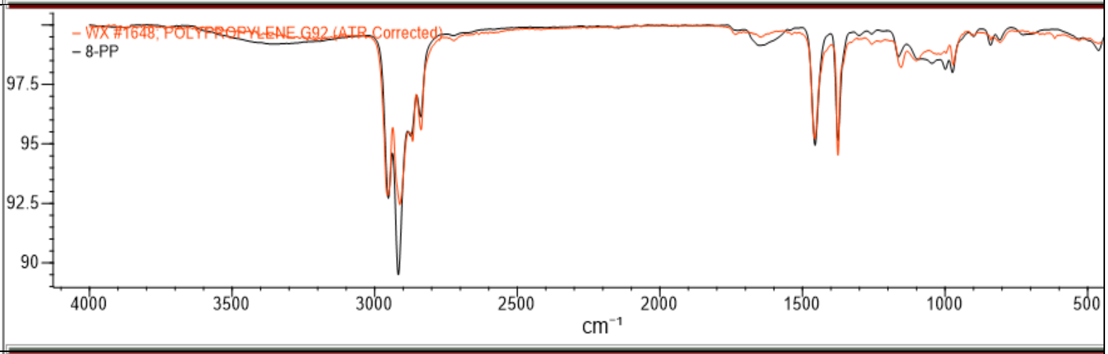
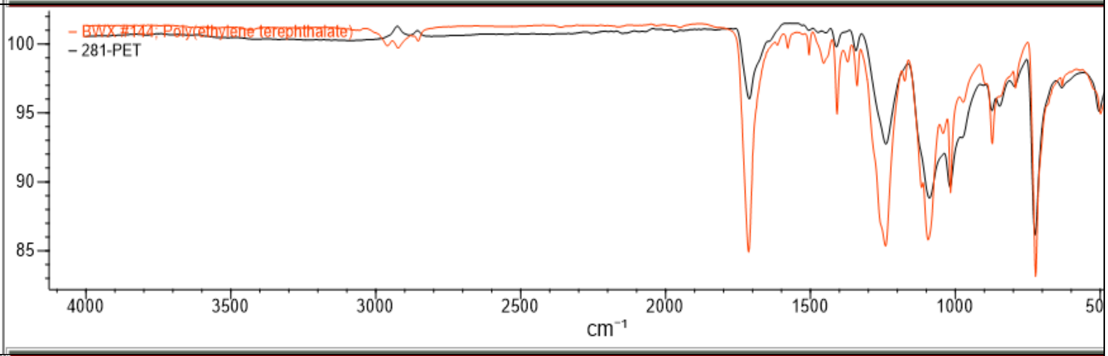
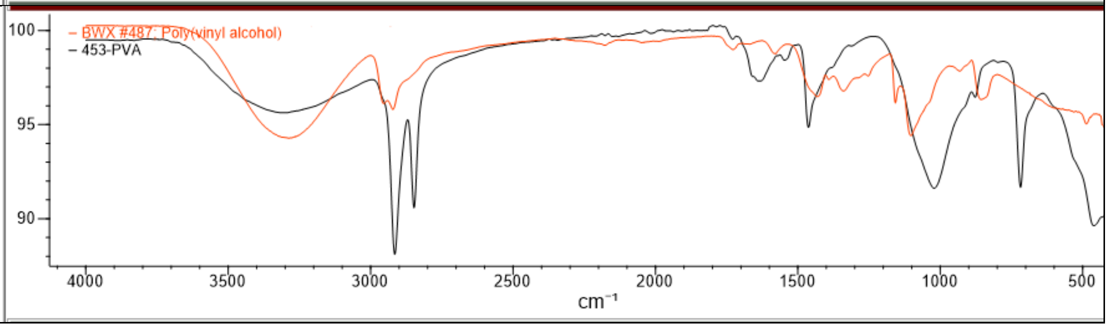
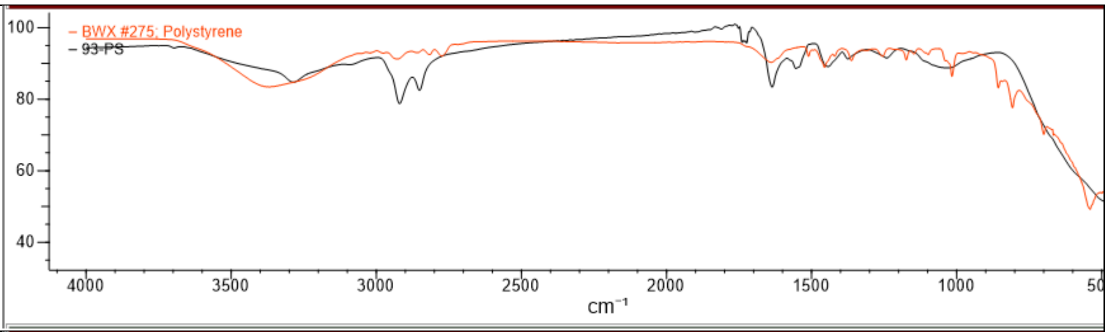
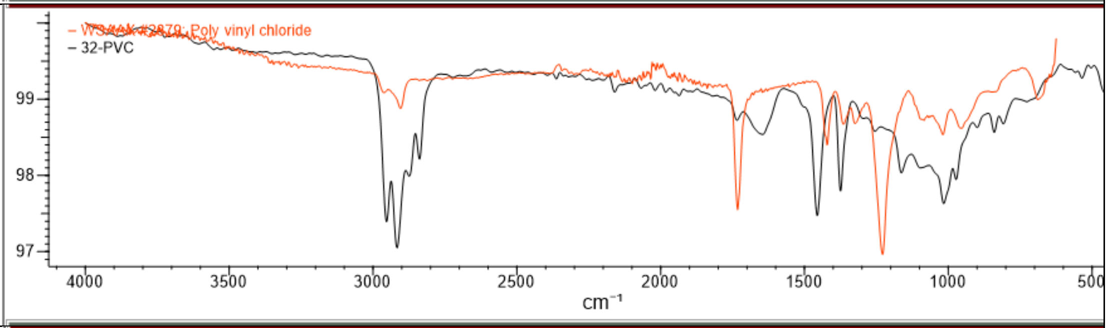
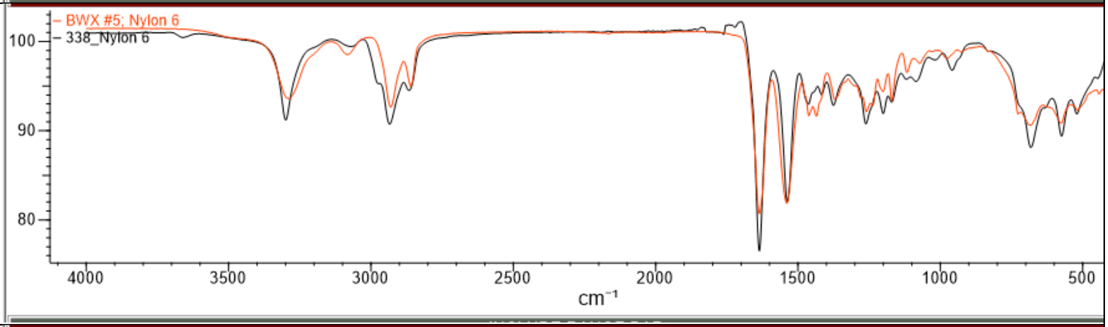
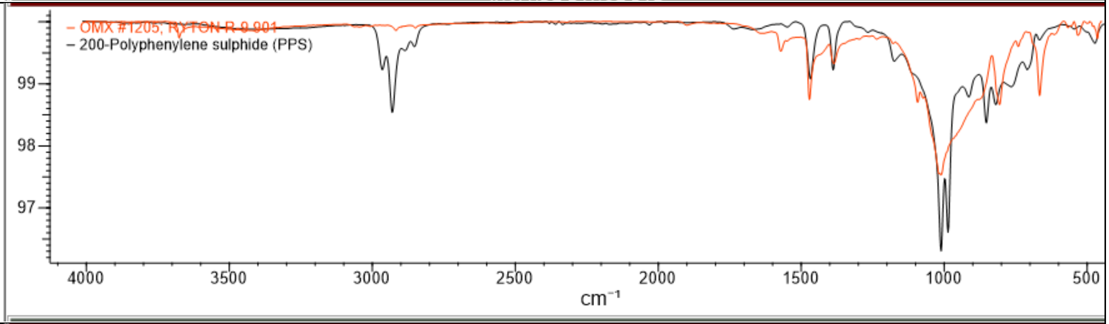
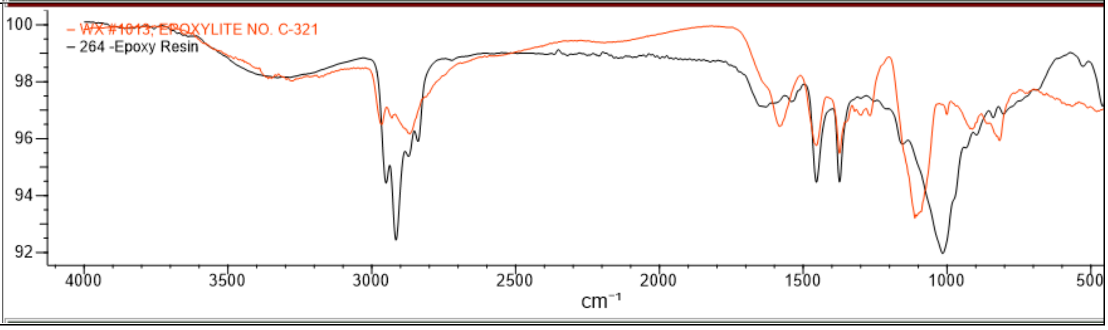
APPENDICES

APPENDIX A: FTIR Spectra of identified microplastic polymers

PE	
PP	
PET	
PVA	

PS	
PVC	
Nylon 6	
PPS	
EP	

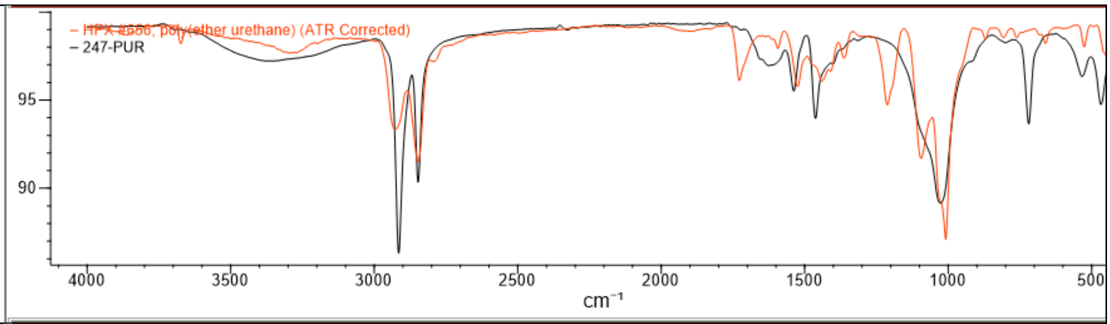
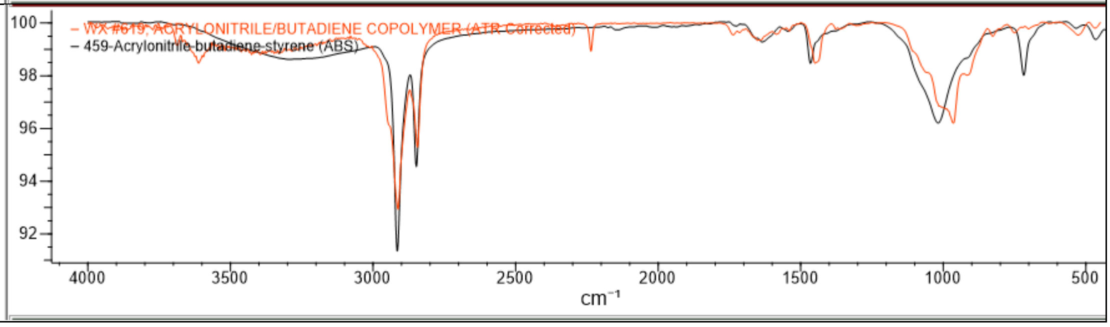
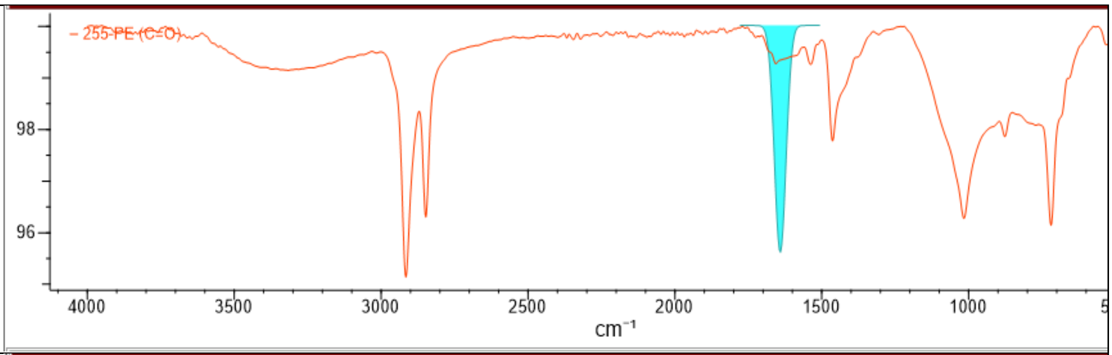
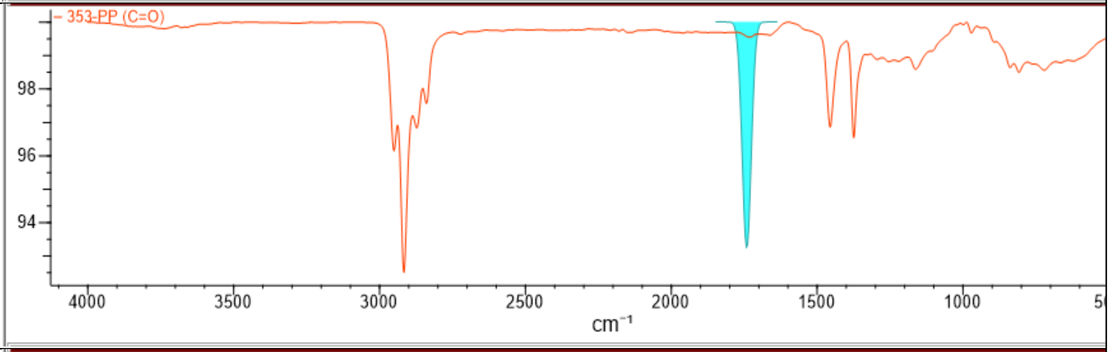
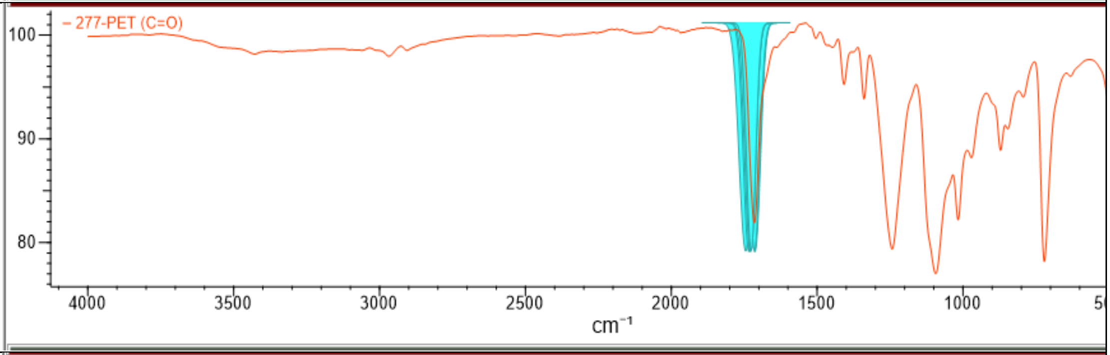
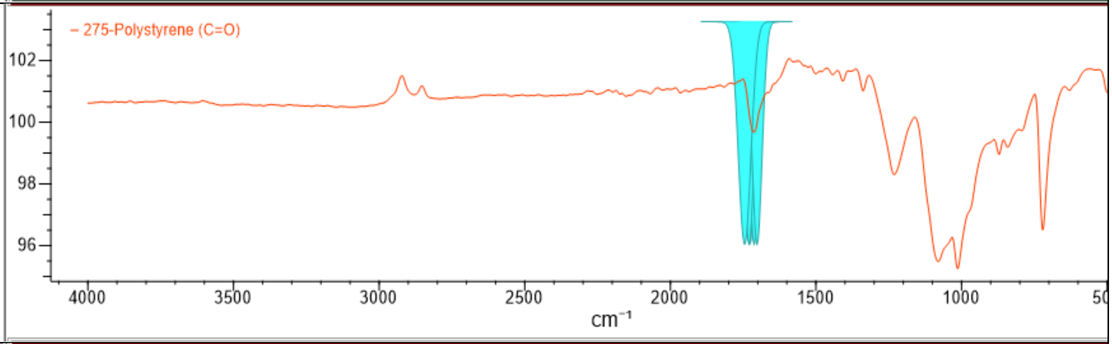
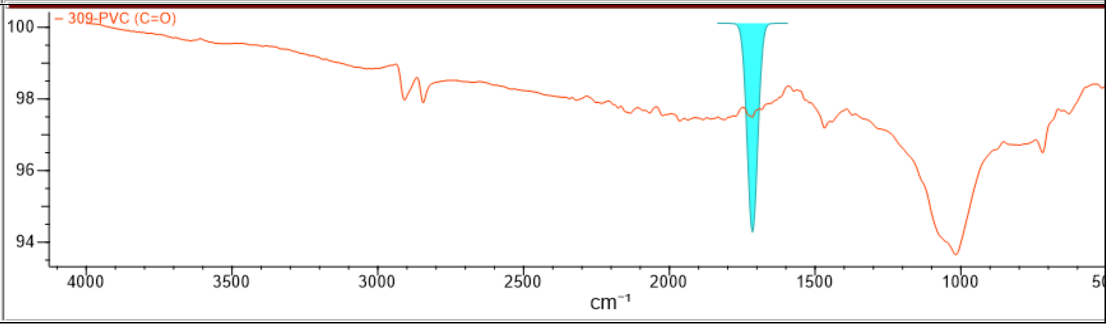
PUR	
ABS	

Figure A.1: FTIR spectra of representative microplastic polymers identified in the river sediments. Vertical axis represents percentage of transmittance and horizontal axis represents wavenumbers (cm-1).

PE	
PP	
PET	
PS	
PVC	

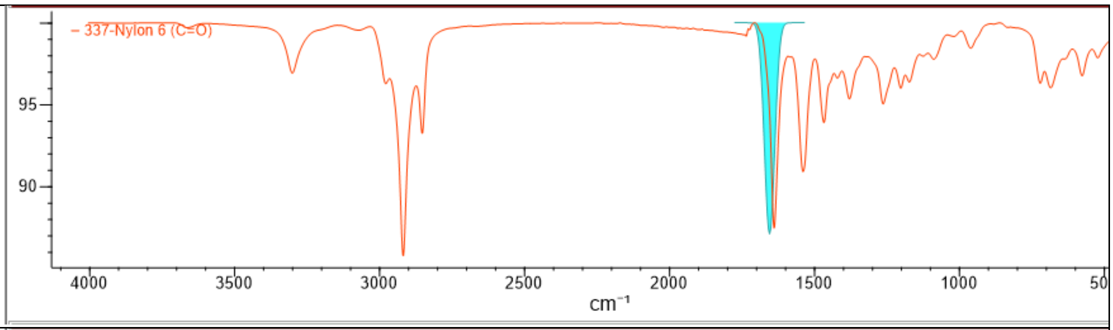
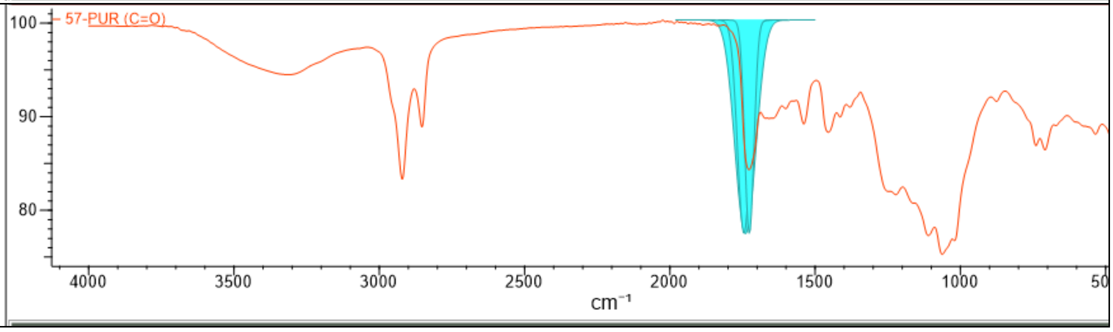
Nylon 6	
PUR	

Figure A.2: FTIR spectra with carbonyl group in the polymer chain of representative microplastics identified in the river sediments. Vertical axis represents percentage of transmittance and horizontal axis represents wavenumbers (cm-1). Light Cyan downward bell curve indicates the presence of carbonyl group in the FTIR spectrum.

APPENDIX B: Summary of the Literature Review

Table B.1: Overview of sample collection techniques of microplastics in the river sediment.

No.	Sediment Type	Collection Tool	Sampling Method	Depth (cm)	Area (m^2)	Mass/Volume (gm)	References
1	Riverbed	Van Veen grab	Bulk	2	-	945	Eo, 2019
2	Between the shoreline and water edge	stainless steel shovel.	Bulk	2	0.04	200	Jiang et al., 2019
3	River shore	steel trowel	Volume-reduced	1	-	-	Constant et al., 2020
4	Riverbed	ven veen grab	Bulk	10	-	-	Simon-Sánchez et al., 2019
5	Shoreline	Van Veen grab	Bulk	12	0.051	-	Rodrigues, 2018
6	Riverbed	Peterson sampler	Bulk	10	-	2000	Su et al., 2018
7	Shoreline	shovel	Bulk	5	-	1000	Wen et al., 2018
8	Riverbed	grab (B-10104, Ravene)	Bulk	-	-	-	Ding et al., 2019
9	Riverbed	van Veen sampler	Bulk	5–10	-	200	Gerolin, 2020
10	Riverbed	Box corer	Bulk	20	-	1000	Wu et al., 2020
11	Riverbank	Cole–Parmer sediment sampler	Bulk	15	-	500	Tien et al., 2020
12	Riverbed	Ponar stainless-steel grab sampler	Bulk	0-3	-	-	He et al., 2020
13	Shoreline	stainless steel spatula	Bulk	0-5	-	-	Feng et al., 2020

No.	Sediment Type	Collection Tool	Sampling Method	Depth (cm)	Area (m^2)	Mass/Volume (gm)	References
14	Riverbed	Peterson grab sampler	Volume-reduced	0-15	-	500	Wang et al., 2018
15	Midpoint,shore and riverbank	Peterson grab sampler	Bulk	5	-	-	Liu et al., 2021
16	Riverbank	shovel	Bulk	-	-	500	Peng et al., 2018
17	Riverbed	grab bucket (B-10104, Ravenep	Bulk	0-10	-	5000	Huang et al., 2020
18	Riverbed		Bulk	5	-	2000	Nel et al., 2018
19	Riverbank	stainless-steel shovel	Bulk	4-5	100	-	Sekudewicz et al., 2020
20	Shoreline	stainless-steel shovel	Bulk	2	400	-	Wang et al., 2017
21	Riverbed	Van Veen grab sampler	Bulk	5	-	2000	Lin et al., 2018
22	Riverbed	grasp bucket	Bulk	-	-	-	Fan et al., 2019
23	Shoreline	stainless-steel spoon	Bulk	0-5	-	1000-2000	Amrutha and Warrier, 2020
24	Riverbed	Perspex tubes	Bulk	50			Niu et al., 2021
25	Riverbed	Quadrat	Bulk	5		2000	Nel et al., 2018
26	Shoreline	Stainless steel scoop	Bulk				Horton et al., 2017
27	Middle and both sides of the bow	Grab dredge and stainless-steel shovel	Bulk	5			Zhang et al., 2020

Table B.2: Overview of Sample Analysis techniques of microplastics in the river sediment.

No.	Sampling Device	Container	Drying Temp. (oC)	Size Selection	Digestion	Density Selection	Filtration	Visual Inspection	Identification	References
1	Van Veen grab	Amber glass bottle	60	20 µm metal sieve	Fenton's reagent	Lithium metangstate	Polycarbonate filter paper (5 mm, 47 mm Ø)		FT-IR	Eo, 2019
2	Stainless steel shovel.	Aluminium foil and sample box	70	2 mm stainless sieve	Wet peroxide oxide	Zinc Chloride	0.22-mm pore size GF/C filter	Stereoscopic microscope	Raman spectroscope	Jiang et al., 2019
3	Steel trowel	Glass bottle		A column of sieves (5, 2.5, 1 mm; 500, 315, 63 µm)		A hypersaline solution	Whatman® filter papers	Dissecting stereo-microscope	FT-IR	Constant et al., 2020
4	Ven Veen grab	Glass container		2mm, 63 µm sieve	Wet Peroxide Oxide	Saturated NaCl solution	Glass-fiber filter (GF/F; 47 mm ø, 0.7 µm pore size)	Stereomicroscope	µFT-IR	Simon-Sánchez et al., 2019
5	Van Veen grab	Aluminium foil and sediment box	90	0.055 mm sieve	Fenton's reagent	Zinc Chloride	0.45 µm clean membrane filter	Stereo microscope Optika	ATR–FTIR	Rodrigues, 2018
6	Peterson sampler	Glass bottle, aluminum pot and	65	20 micrometer nylon filter	Hydrogen peroxide	Saturated sodium chloride solution	20 micrometer nylon filter	Microscope	µFT-IR	Su et al., 2018

No.	Sampling Device	Container	Drying Temp. (oC)	Size Selection	Digestion	Density Selection	Filtration	Visual Inspection	Identification	References
		aluminum foil bag								
7	Shovel	Aluminum foil and bag	65		Fenton's reagent	Zinc chloride granules	Vacuum-filtered onto a GF/C filter	Scanning electron microscope	Micro-Raman spectroscopy	Wen et al., 2018
8	Grab (B-10104, Ravene)		70		30% Hydrogen peroxide	NaCl solution	0.45 µm filter paper	Metallographic microscope	SEM	Ding et al., 2019
9	Van Veen sampler		50	63-µm stainless steel mesh	30% Hydrogen peroxide	ZnCl2 solution	Filter-paper (pore: 18 µm)	Motorized stereomicroscope	Software AxioVision	Gerolin, 2020
10	Box corer	Aluminum foil bags			Wet Hydrogen peroxide	ZnCl2 solution	0.45 µm GF/C glass microfiber filter membranes	Fluorescence microscopy	FT-IR, µ-FT-IR and SEM	Wu et al., 2020
11	Cole–Parmer sediment sampler	Glass bottles	50	mesh sieves (50–297 µm and 297–5000 µm)	35% Hydrogen peroxide	Zinc chloride solution	Filter membranes (47 mm diameter and 0.8 µm pore size)	Dissecting microscope	FT-IR	Tien et al., 2020
12	Ponar stainless-steel grab sampler	Glass jars				Zinc chloride (ZnCl2)	Acuum filtration (0.45 µm membrane filter)	Light microscope	FT-IR	He et al., 2020
13	stainless steel spatula	Aluminum foil bag	70	2 mm stainless sieve	30% Hydrogen peroxide	Saturated NaCl	GF/C filters (0.45µm pore size, 47mm diameter)	Stereoscopic microscope	Raman spectroscope	Feng et al., 2020

No.	Sampling Device	Container	Drying Temp. (oC)	Size Selection	Digestion	Density Selection	Filtration	Visual Inspection	Identification	References
14	Peterson grab sampler		60	5 mm stainless steel mesh	30% Hydrogen peroxide	Zncl2 solution	4 micrometer polycarbonate membrane filter	Fluorescence stereo microscope	μFT-IR	Wang et al., 2018
15	Peterson grab sampler	Aluminum boxes	air-drying		30% Hydrogen peroxide	Saturated NaCl solution	Whatman GF/C glass fiber filter (pore size = 1.2 micrometer)	Stereo microscope	μ-FT-IR	Liu et al., 2021
16	Shovel	Tin cup or aluminum foil	70			Saline solution of NaCl	Filter paper (Whatman GF/B, 4 ¼ 1 mm)	Stereo microscope	m-FTIR	Peng et al., 2018
17	Grab bucket (B-10104, Ravenep		70		30% Hydrogen peroxide	Saturated salt solution	0.45 μm filter paper	Metallographic microscope	AT-FTIR	Huang et al., 2020
18			50	2 mm mesh steel sieve		Hyper-saturated saline solution	63 μm mesh	Olympus dissecting microscope		Nel et al., 2018
19	Stainless-steel shovel	Glass container	40			NaCl solution	Metal sieves (5, 0.75 and 0.30 mm) and filtered	Stereo microscope	Raman/FT-IR and SEM	Sekudewicz et al., 2020
20	Stainless-steel shovel	Aluminium foil bag	50			Saturated NaCl	Glass microfiber filter (Whatman GF/B, diameter 47mm, pore size 1μm)	Digital handheld microscope	μ-FTIR, SEM and ICP-MS	Wang et al., 2017

No.	Sampling Device	Container	Drying Temp. (oC)	Size Selection	Digestion	Density Selection	Filtration	Visual Inspection	Identification	References
21	Van Veen grab sampler	Aluminium foil bag	60		10% KOH	Saturated NaCl solution	20 µm membrane filter	Stereo light microscope	µ-FTIR	Lin et al., 2018
22	Grasp bucket	Wrapped with aluminum foils, and sealed in ziploc bags		1 mm, 0.45 mm and 0.1 mm mesh sieves		Potassium formate (KF) solution	8 µm cellulose nitrate membrane filter	Stereomicroscope	µ-FTIR and Raman spectroscopy	Fan et al., 2019
23	Stainless-steel spoon	Aluminum container, and aluminum foil.	90	0.3 mm and 5 mm sieves	Fenton's reagent	Zinc chloride solution	0.3 mm sieve	Stereozoom Microscope	FT-IR attenuated total reflectance (ATR) unit	Amrutha and Warrier, 2020
24	Perspex tubes	Glass Container	90	metal mesh screens (0.3-5.0 mm)	Fenton's reagent	saturated NaCl solution	Whatman GF/B glass microfiber filter (pore size 1.0 µm)	stereo microscope	Fourier-transform infrared spectroscopy attenuated total reflectance (FTIR-ATR) and SEM	Niu et al., 2021
25	Quadrat	Ziplock bag	50	2 mm mesh steel sieve		hyper-saturated saline solution	63 µm mesh	Olympus dissecting microscope		Nel et al., 2018
26	Stainless steel scoop	Glass Kilner jar	80	1–2 mm and 2–4		$ZnCl_2$ solution	1.2 µm Whatman GF/C glass	binocular light microscope	Raman spectroscopy	Horton et al., 2017

No.	Sampling Device	Container	Drying Temp. (oC)	Size Selection	Digestion	Density Selection	Filtration	Visual Inspection	Identification	References
				mm sieve			microfibre filter papers			
27	Grab dredge and stainless steel shovel	aluminum foil sample bags	60		hydrogen peroxide	saturated sodium chloride solution	0.45 µm filter membranes	Magnifying glass (10×) and Vertical optical microscope	micro-Fourier transform infrared (FTIR) spectrometer	Zhang et al., 2020

Table B.3: Overview of abundance and characteristics of MPs.

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
1	Nakdong River, South Korea	Mean: 1971 particles/kg dry weight	< 300 µm -81%	Fragments -84%, Fibers -15% and Spheres (1%).	PP- 24.8%, PE- 24.8%, PES- 5.5%, PVC - 5.4%,PS 5.3%, Acrylic - 4.6%, Polydimethylsiloxane- 4.5%, PU- 3.9%, Poly(acrylate-styrene)- 3.7%, Poly(lauryl acrylate) -3.6% and others <3%		Eo, 2019
2	Rivers of the Tibet Plateau	Range: 50±7 item/kg to 195±64items/kg	<1mm - 70%	Fiber -53.8% to 80.6% and Pellets or Fragments- rest	Polyethylene terephthalate (PET) - most abundant.	Transparent- 30% to 50%, Black- 18% to 30%, White- 4% to 10%, Red- 6% to 18%, Blue- 3% to 32% and Green- 0 to 8%	
3	Têt river, perpigan, france	Mean: 258 ± 259 item/ kg		Fragments -54.8%, Fibers -19.5%, Foams -13.0%, Films -7.0% and Beads -5.7%	Fibers: Non-plastic - 40%; Fragments: PE- 45%, PP- 23% ; Films: PE- 29%, PP- 35%; Foams: PS- 50% and Beads: PE- 100%		Jiang et al., 2019

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
4	Ebro River, spain	Range: 1491 ± 272 particles/kg dry weight to 2899±718 particles/kg dry weight	<50 µm: 2.5%, 50-100µm: 4%, 100-200µm: 11.5%, 200-500µm: 30%, 500-1000µm: 18%, 1000-2000µm: 18%, 2000-3000µm: 9% and >3000µm: 7%	Fiber>Fragment>Film>Foam	Polyamide -24%, Polyethylene- 16%, Poly(methyl methacrylate)(acrylic)-12%, Polyester- 12%, Polypropylene- 8% and Polyacrylate- 4%	Colour- 58%, Transparent-20%, Black- 10% and White- 2%	
5	Antuã River, Portugal	Range: 18 to 629 items/kg dry weight		Fragments- 43.6% (most) and Pellets- 1.2% (lowest)	PE- 29.4%, PP- 29.4%, PS- 8.8%, PET- 8.8%, Others- 29.4%	Colour(blue,green)>White>Black>Transparent	Constant et al., 2020
6	Middle-Lower Yangtze River Basin	Range: 15 to160 items/kg	0.25-1 mm - Most abundant	Fiber>Fragment>Film>Pellet	Polyester- 33%, Polypropylene- 19% and Polyethylene- 9%	Transparent and blue items- Most abundant	
7	Xiangjiang River	Range: 270.17 ± 48.23 items/kg to 866.59 ± 37.96 items/kg	<0.5mm: 21% to 52%, 0.5-1mm: 12% to 29%, 2-3mm: 5% to 12%, 3-4mm: 3% to 12% and 4-5mm: 2 to 40%	Fragment- 50.82%, Fiber- 28.15%,Film- 18.14% and Foam<10%	PET- 14.71%, PP- 13.24%, PE- 19.12%, PA-10.29%, PS- 19.41%, PVC- 7.35%, Non-plastic- 5.88%	Transparent- 16% to 50%, White- 4 to 40%, Red- 2 to 32%, Blue- 4% to 23%, Green- 4% to 23% and Yellow- 0 to 8%	Simon-Sánchez et al., 2019
8	Wei River,china	Range: 360 to 1320 items/kg	< 0.5 mm: 40.8% to 68.8%, 0.5-1mm: 8.35% to 24.2%	Fiber- 42.25% to 53.20%, Film- 23.9% to 31.8%, Fragment- 10.2% to 20.3%, Pellet 5.6%-16.1%, Foam- 0.7% to 3.5%			

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
9	Amazon rivers, Brazil	Range: 417 to 8178 particles/kg of dry weight (particles 0. 063–5mm) and 0 to 5725 particles/kg of dry weight (particles 0.063–1 mm)	0-1mm: 3 to 70%, 1-2mm: 23 to 72%, 2-3mm: 5 to 28%, 3-4mm: 0 to 7%, 4-5mm: 0 to 11%				Rodrigues, 2018
10	Maozhou River, china	Range: 35 ± 15 to 560 ± 70 item/kg sediments in April; 25 ± 5 to 360 ± 90 item/kg sediment in October	0.1-1mm: 47.5% to 72.9%	Fragment- 89.4%, Foam- 6.7%, Fiber- 2.3%, Film- 1.6%	PE- 45%, PS-34.5% and PP- 12.5%	Transparent- 38%, White- 28%	
11	Fengshan River	Range: 508 to 3,987 items/kg	Small size: 67% to 96%	Fiber - 61% to 93%	Epoxy resin- 17%, Phenolic resin - 13%, PET- 17%, PE- 8%, PVOH-8%, PI- 7%, PS-6% and PTFE- 6%		Su et al., 2018

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
12	Brisbane River sediments, Australia	Range: 10 to 520 items/kg	PE: <1mm: 22%, 1-2mm: 20%, 2-3mm: 21%, 3-4mm:19% and 4-5mm:18%; PA: 2-3mm: 4% and 3-4mm:96%;PP: <1mm: 12%, 1-2mm: 23%, 2-3mm: 20%, 3-4mm:13% and 4-5mm:32%; Others: <1mm: 28%, 1-2mm: 50% and 2-3mm: 22%	Film>Fragment>Fiber	PE-70%, PA- 12% and PP- 10%	White - Most abundant	
13	Tibetan Plateau	Range: 20−160 items/kg; mean: 60.8±25.06 items/kg	20-50 µm- 25.83%,50-100 µm: 31.79%, 500 -1000µm 11.26% and >1000 µm -4.65%	Fiber- 42.38%, Fragment- 25.16%, Film- 11.92%, Sphere- 11.26% and Foam 9.27%	PP-32.45%, PE 28.48%, PS 15.23% and PET 13.24%	Transparent-45.69%, white-18.54% , black and blue- 15.23% and others - 20.53%	Wen et al., 2018
14	Wen-Rui Tang River, southeast china	Mean: 32947±15342 items/kg	20-300 µm :84.6%, 300-5000 µm: 15.4%	Fragment- 45.9%, Foamp- 29.5%, Pellets- 12.8% and Fibers-11.7%	PE,PP,PES,PS- Most abundant		
15	Haihe River	Range: 1346 to 11917 items/kg dry weight (dw) average: 4980± 2462 items/kg dw	500-1000 µm: 26.5±12.8% (range: 3.7-50.9%), 200-500 µm:24.7±14.3% (range: 1.9-71.5%) and 1000-2000 µm:23.7±12.7% (range: 1.4-70.4%)	Fibers- 70.9% Fragments- 15.8%, Lines- 5.7%, Films- 4.2% Pellets- 3.3%	PE- 49.3% (LDPE-90.7% and HDPE-9.3%), PP- 32.9%, poly(ethylene-propylene) copolymer- 6.4%, PS-5.9% and cellulose- 5.5%	Black- 47.1%, Green- 22.3%, Red- 17%, Transparent-7.4%, White-6.2%	Ding et al., 2019

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
16	Shanghai, China	Mean: 802 ± 594 items kg-1 dry weight	<100mm: 31.19%, 100-500mm: 62.15%, 500-1000mm:3.56%, 1000-5000mm: 2.8% and > 5000mm- 0.3%	Spheres- 88.98%, Fiber- 7.55% and Fragments- 3.47%		White spheres - 90%, Blue- 3%, Transparent- 3%, White- 2% and Red 2%	
17	WestRiver downstream ,china	Range: 2560 to 10240 items/kg	<0.5mm 87-92%, 0.5-1.0mm 6-9% and 1-5mm -2-4%	Fiber 48%-76% Fragment 4%-17% Film 12%-23% Pellet 8-12%	PP - 38%, PE- 27% PS-16%, PVC- 6% PET 4% Non-microplastics -9%		Gerolin, 2020
18	Bloukrans River system	Mean: 160.1±139.5 items/kg					
19	Vistula River (Poland)	Range: 190 items/kg to 580 items/kg	0.3 – 0.75 mm: Most abundant	fiber- 93% (Most abundant)	PS,PP,PE,Nylon- Most abundant	Black- 24% to 68%, Blue- 5 to 22%, Transparent- 6 to 11%, Red- 0 to 13%, Grey- 0 to 21%, Yellow- 0 to 4%, Pink- 0 to 41%, Green- 0 to 4%	Wu et al., 2020
20	Beijiang River	Range: 178±69 items/kg to 544±107 items/kg			PE- 41.7±18.9% to 65.5±11.0%, PP-17.2±2.6% to 33.3±6.6%, Copolymer-5.6±0.8% to 18.8±4.3% and others- 5.3±0.8% to 10.3±8.1%		

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
21	Pearl River along Guangzhou City, China	Range: 80 to 9597 items/kg, mean: 1669 items/kg	0.02–1 mm: 65.3%, 1–2 mm: 29.5%, 2–3 mm: 7.6%, 3–4 mm: 3.3% and 4–5 mm:1.6%	Fiber- 54.7%, Fragment- 43.3% and Film- 43.3%	PE- 47.6% and PP- 26.2%	Yellow- 36.2%, White- 26.8% and Black- 11.7%	Tien et al., 2020
22	Pearl River catchment, China	Mean: 685 ± 342 items/kg dry weight	<0.1mm- 45.0 ± 4.3%, >1mm- 64.5 ± 7.0%	Sheets- 70.0±4.2% (Most abundant)	PP- 2% to 39%, PE- 3% to 40% and PP-PE copolymers- 0% to 6%	White/transparent - 51 ± 7% (Most abundant)	
23	Netravathi River,India	Average: 96 items/kg of dry weight	1-5 mm: 34.6% and 1-0.3 mm: 65.4%	Fragments- 44.4 %, Fibres- 34.6 %, Films- 8.7 % and Foams and Pellets- < 1%	PE- 56.99 %, PET- 23.43 % and PP- 4.20 %	White- 32.2 %, Transparent- 29.0 % and others (black, red, blue, brown, green and yellow)- < 10 %	He et al., 2020
24	Qinhuai River	Range: 163-563 items kg-1 wet sediments	In 1st Layer: 4-5mm: 40.5%, In 3rd Layer: -2-4mm: 41.9%, In 5th Layer: < 2mm: 63.5%	Fragment- 51.3%, Fiber 45.5%	PE-48%, PP- 32%, PMMA- 11%, PU- 5%	Transparent - 35.9%, Green- 20.5%	
25	Bloukrans River, South Africa	Summer: 6.3 ± 4.3 particles kg−1 (mean), Winter:160.1 ± 139.5 particles kg−1 (mean)	-	-	-		Feng et al., 2020
26	Tributaries of the River Thames	Range: 18.5 ± 4.2 to 66 ± 7.7 particles per 100g	1-2mm: 10.2 ± 3.1 to 41.9 ± 3.4 particles per 100g, 2-4mm: 8.1 ± 5.3 to 24.1 ± 5 particles per 100g	Fragment- 49.3%, Fiber- 47.4% and Film- 3.3%	PET - 14 particles, PP- 5 particles, PAS- 5 particles, PE- 2 particles, PS- 1 particle, PVC- 1 particle, Others- 6 particles		

No.	Study area	Abundance	Size	Shape	Chemical Composition	Color	References
27	Qin River	Range: 0 to 97 items·kg−1 dry weight	1-5 mm: 76.0% and 0.03-1 mm: 24.0%	Fibre- 30.9%, Sheet- 62.8% and Fragment- 6.3%	PP- 55.3%, PET- 21.3%, PE- 17.0%	Black- 1.5%, White- 30.0%, Blue- 27.6%, Green- 18.3%, Red- 18.5%, Yellow- 3.5% and Others- 0.6%	Wang et al., 2018

APPENDIX C: Hazard Statement and Shape-Size based distribution of MPs

Table C.1: Density, hazard score and hazard statement of identified MP polymers.

Polymers	**Abbreviations**	**Density (gm/cm^3)**	**Hazard Score (S_j)** (Lithner et al., 2011)	**Hazard Statement (Health, Environmental and Physical)** (Lithner et al., 2011)
Polypropylene	PP	0.85-0.92	1	• Extremely flammable polymer
Polyvinyl alcohol	PVA	1.19-1.31	1	
Polyethylene terephthalate	PET	1.38-1.41	4	• Cause respiratory irritation • Causes skin irritation • Causes serious eye irritation • Harmful if swallowed • Harmful in contact with skin • Harmful if inhaled • May cause drowsiness or dizziness • Harmful to aquatic life with long lasting effects
Polyethylene	PE	0.91-0.97	11	
Polystyrene	PS	1.04-1.08	30	
Nylon 6		1.15	50	
Polyphenylene sulfide	PPS	1.34	**897**	• May cause an allergic skin reaction • May cause allergy or asthma symptoms or breathing difficulties if inhaled • Fatal if inhaled • Causes damage to organs • Very toxic to aquatic life with long lasting effects
Polyvinyl chloride	PVC	1.16-1.41	5001	• May cause genetic defects • May cause cancer • May damage fertility and the unborn child
Epoxy resin	EP	1.14	4515	
Acrylonitrile–butadiene–styrene	ABS	1.0-1.05	6552	
Polyurethane	PUR	1.01-1.21	13844	

Table C.2: Shape-Size based distribution of MPs.

Rivers	**Shape and Size**	**SMPs (<1 mm)**	**LMPs (1-5mm)**
BR (1820)	Fragment	159	181
	Film	122	356
	Fiber	73	19
TR (1994)	Fragment	181	190
	Film	102	449
	Fiber	28	47
BaR (376)	Fragment	24	52
	Film	8	92
	Fiber	1	11
Total (4190)	Fragment	364	423
	Film	232	897
	Fiber	102	77