ABUNDANCE, SPATIAL DISTRIBUTION, AND POTENTIAL SOURCES OF MICROPLASTICS IN HIGH ALTITUDE NAINITAL LAKE, UTTARAKHAND, INDIA

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CERTIFICATE

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DECLARATION

I, **Yashi Jain**, hereby declare that the dissertation project entitled '**Abundance, spatial distribution and potential sources of microplastics in high altitude Nainital Lake, Uttarakhand, India**' submitted to the Department of Ecology and Environmental Sciences, Pondicherry University, in partial fulfilment of the requirements for the degree of Master of Science in Environmental Science is an original research work done by me under the guidance of **Dr. Gurjeet Kaurr**, Assistance Professor, Department of Ecology and Environmental Sciences, School of Life Sciences, Pondicherry University and the co-guidance of **Dr. Hariharan G** (Scientist C), National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, Government of India, Chennai. This work has not been submitted anywhere else to any other institute or publication for the award of Degree/Diploma/Associateship /Fellowship or any other similar title.

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LIST OF ABBREVIATIONS

ATR-FTIR	Attenuated total reflection- Fourier-Transform Infrared Spectroscopy
BOD	Biological Oxygen Demand
CE	Cellulose
FTIR	Fourier-Transform Infrared Spectroscopy
LDPE	Low-density Polyethylene
µFTIR	Micro Fourier-Transform Infrared Spectroscopy
MPs	Microplastics
MT	Metric Ton
Mt	Million tonnes
NMC	Nainital Municipal Council
NY	Nylon
PA	Polyamide
PE	Polyethylene
PL	Polyester
POPs	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PET	Polyethylene Terephthalate
PVAC	Polyvinyl acetate
PVC	Polyvinyl Chloride
RY	Rayon
SBS	Polystyrene Butadiene styrene
SPM	Small Potential Microplastics
SWM	Solid Waste Management
TPD	Tonnes Per Day
TSS	Total Suspended Solids
VPD	Visible Plastic Debris
wPE	Weathered Polyethylene

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ABSTRACT

Microplastic (MP) contamination has been reported in the aquatic environment worldwide, but there is less information available about their presence in freshwater lakes at higher altitudes. Nainital Lake, present at a high altitude in Indian Himalayas, has various ecosystem services. Though this is the only source of water for the residents of Nainital town, the MPs abundance is still unknown. This study presents the first evidence of the abundance and distribution of MPs in and around Nainital. This lake is highly impacted by the inflow of untreated water from the canals into the lake and the tourists' activities. Surface water (13 sites) and surface sediment (7 sites), including hotspot areas (3 sites), were analyzed from 16 different sites in and around the catchment area of the Nainital Lake. The MPs were observed in all the samples, and their concentration ranges from 8.6 to 56.0 MPs/L in lake surface water, 2.4 to 88.0 MPs/L in hotspot areas water, 0.4±0.0 to 10.6±1.56 MPs/g in the lake surface sediment and 0.6±0.49 MPs/g hotspot areas sediment. Fibers were found to be dominating in both the surface water and sediment samples, followed by fragments and films. MPs were observed in all size fractions in the surface water and sediment samples, but their predominance was found in the size range of 0-1 mm. The colored MPs were found to be abundant in both the surface water and sediment samples. The polymer types were analyzed using an ATR-FTIR spectrometer, and PE was found to be abundant in both the surface water and surface sediments. The litter was collected from the hotspot sites in the Nainital Lake, and plastics were found to be the major component. The run-off catchments releasing untreated water into the lake via several drains and tourist activities can be considered as the major source of MPs into the lake and can affect the aquatic fauna and aesthetic value of the lake. The small concentration of MPs observed in the tubewell and drinking water depicts the direct risks to humans and, thus, the need to use smaller size filters to prevent the contamination of drinking water by MPs. The measures should be taken to treat the sewage water before its discharge into the lake. This study fills the gap of MPs in the higher altitude freshwater lakes in India, which can be the major pathway for the transport of MPs to the rivers, and emphasizes the need for waste management in the Nainital town.

Chapter 1

INTRODUCTION

Microplastics (MPs) are plastic particles smaller than 5 mm in size, which are formed by the fragmentation of larger plastic material or are directly used as abrasives in cosmetics and blasting media (Thompson et al., 2004; Fendall and Sewell, 2009), as exfoliating materials in the face and body scrubs. They were initially discovered in the 1970s (Carpenter and Smith, 1972), and are now one of the most significant pollutants found all over the globe (Godoy et al., 2021). Due to their adverse effects on both the environment and the health of organisms, they are considered to be a major threat to the environment. Research has shown that microplastics are ubiquitous and are found in various environmental matrices including freshwater, the atmosphere, and marine and terrestrial sources. Freshwater lakes are semi-closed systems with a longer retention time, which can become the major sinks of microplastics (Pastorino et al., 2022). Due to their small size and resemblance to food particles, they can be consumed by aquatic fauna and are known to transfer into the food web (Nelms et al., 2018). They may have ecotoxicological effects on an organism's body after consumption. Freshwater sources are considered the major sources for transferring microplastics to the marine environment.

1.1 Plastics

Plastics are ubiquitous materials found in various daily life applications such as food packaging and household items, among others (Fendall and Sewell, 2009). They consist of complex molecular compounds formed by the polymerization of tiny monomeric units. The term Plastic means ‘capable of being molded’. Plastic production dates back to the early 20th century. The first entirely synthetic plastic ‘Bakelite’, a phenol-formaldehyde thermoset, was produced in 1907 (Hossain MS et al., 2020) by Belgian Chemist Leo Baekeland, which marked the revolution of plastic production in the world. The mass production of plastics started after World War II, which led to 2 million tons of annual plastics production in the 1950s, and since then, their production has been increasing and is expected to increase more in the future (Geyer et al., 2017). Plastic production has increased from 2 million tons per year in the 1950s to 390.7 million tonnes per year in 2021 (**Fig. 1.1**), with China as the leading producer, producing around one-third of the world’s plastics (PlasticsEurope, 2022). Plastics are strong, durable, lightweight, corrosion-resistant, and low-cost materials, making them useful worldwide. However, these plastics are non-biodegradable materials; thus, they continue to build up in the environment. Their extensive production, use, and mismanagement lead to a large amount of environmental waste.

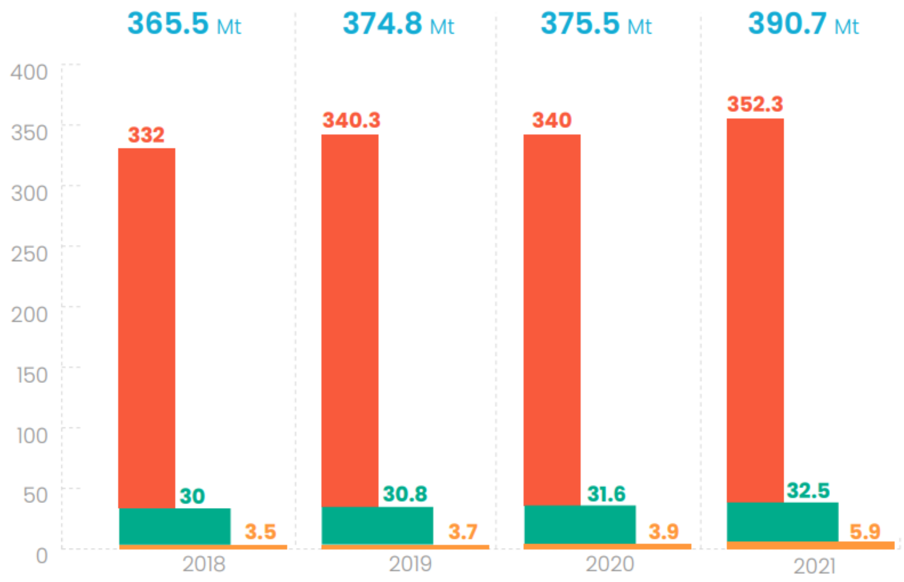


Fig. 1.1: Global Plastics Production (Source: PlasticsEurope, 2022 https://www.plasticseurope.org/en/resources/ market-data)

Even though plastic is used in a wide range of sectors, including electronics, institutions, transportation, industrial machinery, building, and construction, packaging is the primary industry (**Fig. 1.2**) that drives up the use of single-use plastics at the expense of reusable plastics (Geyer et al., 2017). This led to the percentage of single-use plastics in medium- and high-income nations increased from 1% in 1960 to more than 10% in 2005 (Jambeck et al., 2015). Plastic comprises the repeating units of long-chain polymers, which are hydrocarbon derived from petrochemicals. According to their physical characteristics, there are two types of plastics: thermoplastics, or plastics that may flex readily when heated, and thermosetting plastics, or plastics that, once formed, cannot be softened. The thermoplastics include High-density Polyethylene (HDPE), Low-density polyethylene (LDPE), Polystyrene (PS), Polypropylene (PP), Polyvinyl chloride (PVC), and Polyethylene terephthalate (PET). In contrast, thermosetting plastics include Bakelite, epoxy, and Polyurethane (PU).

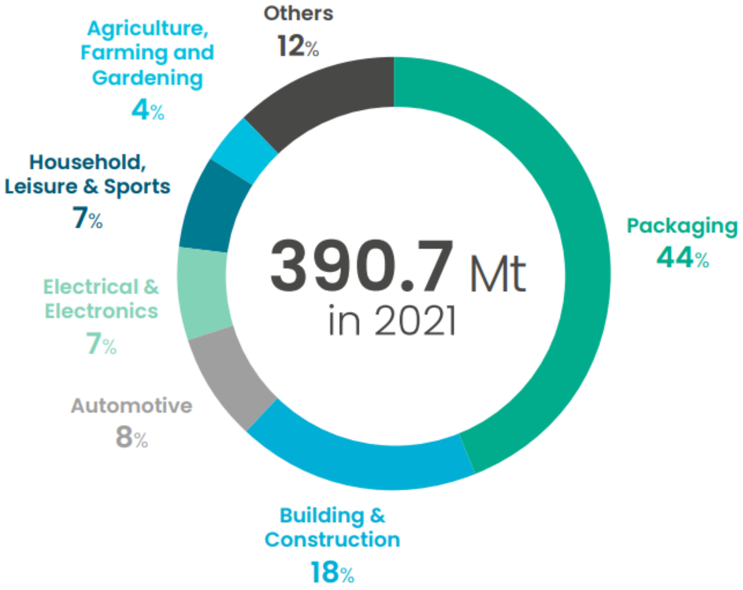


Fig. 1.2: Distribution of the global plastics use by the application (Source: PlasticsEurope, 2022 https://www.plasticseurope.org/en/resources/ market-data)

1.2 Fate of Plastics

Plastic is the fastest-growing waste which is one of the significant factors causing environmental degradation. It is produced worldwide for diverse uses and ends up in the environment and causes pollution. It is one of the most prevalent man-made materials in the twenty-first century, but due to its extensive usage, frequent disposal, and incredibly slow decomposition, it is accumulating in the ocean basins, marine and freshwater ecosystems, and even in remote areas, including the Polar regions (Godoy et al., 2022). The Anthropocene era has been termed the "Plasticene Age" due to the extensive usage of plastics by humans (Jonathan et al., 2021). The plastics remain in the environment for a longer duration, thus polluting the environment for a longer time, which can be a continuous health hazard to plants, animals, and microorganisms (Uurasjärvi et al., 2020).

The current levels of plastic waste are beyond the capacity of most nations. Around 6300 million tonnes of plastic waste have been produced till 2015, out of which approximately 79% of the waste has been disposed of in landfills or the environment (Geyer et al., 2017). According to Borrelle et al. (2020), around 11% (19- 23 million tonnes) of the global plastic waste generated in 2016 entered the aquatic environment, and by 2030 it can reach up to 90 million tonnes per year if the current trend of plastic disposal continues with no improvement in policies. India being the major consumer and producer of plastic waste annually, produces around 9.4 million tonnes of plastic waste (MoHUA, 2019). The uncontrolled disposal of plastics in the environment is a significant threat around the globe. According to an estimate, 75% of the total marine debris consists of plastics only. The plastics have even been found 400 feet below the ocean surface, termed a Blue Hole.

Lakes are no exception for being the garbage dumping sites of plastic waste. Around 80% of litter on the shoreline of great lakes is found to be plastic debris (Driedger et al., 2015), which can harm the aquatic life inside the lake. The large-sized plastic debris can lead to the entanglement of wildlife and also affect other recreational activities by degrading the natural beauty (Opfer, 2013). The large particles have the tendency to break into smaller pieces that may be consumed by aquatic fauna and, thus, can enter the food chain, where they might cause adverse consequences. The discharge of plastic debris by tourists has an impact on the sensitive ecosystem of the high-altitude mountains. So, the plastic waste that accumulates in the mountains makes its way into the ground, rivers, or freshwater lakes, where it meets the ocean and sea, thereby polluting the marine ecosystem. Plastic waste can also accumulate harmful, persistent organic pollutants by adsorbing them onto their surface, which, if ingested, can be dangerous for the health of the organisms.

1.3 Microplastics

The plastic, once formed, cannot be degraded, thus, it eventually breaks into small fragments, and the molecules remain intact, thus maintaining its identity. The plastics get fragmented over time into particles smaller than 5mm, which are termed microplastics, which is due to mechanical, photolytic, and biological forces (Arthur et al., 2009; Karthik et al., 2018) acting on the plastics present in the environment. The MPs can be formed either by the fragmentation of the macroplastics (large-sized plastic material) or from the abrasives being used in cosmetics and blasting media (Thompson et al., 2004; Fendall and Sewell, 2009).

The shift of cosmetic products such as natural skin cleansers to microbeads containing skin exfoliating material (Fendall and Sewell, 2009) has increased the load of MPs in the environment. The other sources include washing textiles, toothpaste, tires, city dust, marine coatings, and road markings. These MPs are released from many sources by drainage from urbanized and industrial regions or by direct discharge into the environment, where they eventually find their way into terrestrial or aquatic sources. Recent research has shown that

MPs may be transported to many parts of the planet by the wind, ocean currents, and sea ice. As MPs may be found in deep-sea sediments, snow, glaciers, freshwater ecosystems, and beach sediments, they can be regarded as ubiquitous.

The distribution of MPs mainly depends on the population density, urbanization, and industrialization around the catchment areas (Klein et al., 2015). The release of MPs into freshwater sources depicts their transfer into the food web. These MPs have sediment size fraction and can resemble planktons, thus can be consumed mistakenly by many marine organisms (Sivan, 2011; Wright et al., 2013), that can penetrate and accumulate in the food chain (Betts, 2008; Thompson et al., 2009), and cause physical injuries such as blockages and internal abrasion (Wright et al., 2013). The impacts of ingesting MPs on organisms are mostly influenced by particle size, shape, concentration, and chemical characteristics such as hydrophobicity and the presence of microbial biofilms (Bhatt et al., 2021). The contamination of the freshwater ecosystem by MPS has now become a global issue.

1.3.1 Categorization of Microplastics

The MPs can be primary or secondary based on their source of generation. Primary MPs are used produced intentionally for use as industrial raw materials or can be used in cosmetics (Singh and Sharma, 2008) as skin cleansers or 'exfoliating material' containing microbeads (Fendall and Sewell, 2009), whereas the fragmentation of larger plastic objects forms secondary microplastics by physiochemical or biological breakdown, atmospheric agencies, UV radiation, or mechanical degradation (Singh and Sharma, 2008).

According to their morphology, the MPs are primarily divided into five categories as fibers, pieces, pellets, film, and foam. The breakdown of larger plastic objects by mechanical forces forms fragments, degradation of plastic bags or packaging materials produces films, personal care products, and pre-production plastics produce pellets; fibers are released from textile washing which has a width-to-length ratio of 1 to ≥ 1.5 (Obbard, 2018), and foam is released by the breakdown of larger thermocol materials. However, anthropogenic sources, including rayon, nylon, wool, cotton, and silk, release fibers into the environment (Obbard, 2018). According to Browne et al. (2011), synthetic fabrics can release up to 1900 fibers per garment on washing.

The plastics on the basis of their polymerization include Polyethylene (PE), Polypropylene (PP), Polyamide (PA), Polyvinyl Chloride (PVC), Polystyrene Butadiene styrene (SBS), Rayon, Nylon, Thermoplastic Polyurethane, Ethylene Propylene rubber (Obbard, 2018).

Polyolefins, i.e., PE and PP, account for almost half of all manufactured plastics and are often single-use materials (PlasticsEurope, 2022). Also, PVC includes a major share of plastics production. Numerous synthetic polymers, like PP and PE, float on the top of the water because they have lower specific gravity than seawater, but denser plastic polymers, like Nylon, PET, and PVC, have a tendency to sink to the bottom of the water column (Andrady, 2011; Engler, 2012), from where they might be carried to other locations by water currents.

1.3.2 Presence of MPs in the Environment

The MPs created by industry applications directly or by the fragmentation of bigger polymers are released into the environment. Microplastic abundance in the marine environment dates back to the early 1970s (Carpenter et al., 1972). Since then, the MPs have been studied in various environments, such as oceans (Andrady, 2011; Jambeck et al., 2015; Carbery et al., 2018; Robin et al., 2019), beaches (Van et al., 2012; Karthik et al., 2018), sediments (Dekiff et al., 2014; Vaughan et al., 2017), river (Wang et al., 2017; Buwono et al., 2021), glaciers (Ambrosini et al., 2019; Cabrera et al., 2020), and atmosphere (Dris et al., 2015; Z. Liu et al., 2022). MPs are now one of the major components of the environment, which are found even in remote areas, from the Arctic to the Antarctic, mountains to deep-sea sediments. The studies show that the Arctic Sea is the main sink for the MPs.

Microplastics can enter the environment directly by sewage discharge, industrial discharge, or direct untreated discharge into surface waters, especially in developing nations (Velasco et al., 2020). These surface waters also come into contact with the marine environment, where they might later enter the food chain. Growth and development in developing nations are causing improper environmental disposal of plastic waste, the majority of which is dumped in landfills. Floods, glacier melting, atmospheric deposition, and other natural disasters all significantly contribute to the leakage of MPs into water bodies. Plastic fragments break down as a result of global warming, which may potentially increase the number of MPs in the environment.

These MPs have sediment size fraction and can resemble plankton; thus, can be consumed mistakenly by many marine organisms (Sivan, 2011; Wright et al., 2013) and can enter the food web. The studies show the trophic transfer of MPs among the organisms (Nelms et al., 2018), including plankton, fishes, seabirds, molluscs, and crustaceans. These MPs have been studied to have harmful impacts on wildlife and humans. Since the MPs have a large surface area per unit mass/volume, thus they can act as vectors (Retama et al., 2016), thus adsorbing various toxic chemicals or additives (Mason et al., 2016), which can enter the body of the aquatic organisms via water, food or sediments. While manufacturing plastics, additives like plasticizers, flame retardants, and extenders are used to give the polymers certain qualities that are thought to be detrimental to the environment and living organisms.

1.4 MPs in the freshwater lakes

MPs are said to be ubiquitous since they can be found in every aspect of the globe, from surface to deep waters, mountains to glaciers, and in the atmosphere to rain. There have been several studies on the prevalence and abundance of MPs in the marine environment, sediments, and beaches, but there is only a small amount of data available for freshwater lakes. The contamination of freshwater lakes with MPs has been studied in different parts of the world, including Russia (Malygina et al., 2021), Switzerland (Velasco et al., 2020), India (Gopinath et al., 2020; Tsering et al., 2022; Laju et al., 2022), China (Zhang et al., 2016), and Spain (Godoy et al., 2022).

According to Pastorino et al. (2022), freshwater lakes can function as the main sinks of MPs since they are a semi-closed system with a long retention time. Compared to seas and coastal areas, freshwater lakes have different hydrographic conditions that can deposit MPs in significant volumes (Sighicelli et al., 2018). MPs are studied in lake sediment, lake bottom, and lake water. The aquatic fauna in freshwater lakes may unintentionally consume the MPs as food particles, allowing them to move through the food web. The presence of MPs in the lake is mostly influenced by factors including height, depth, wind direction, population density, and precipitation (Koutnik et al., 2021). The MPs are released straight into lake waters because of the lack of disposal facilities in remote areas, where they ultimately sink to the lake bottom (Yang et al., 2021b).

According to Hoffman and Hittinger (2017), annually, around 10,000 tonnes of plastic waste enter the Great Lakes, making the issue of Plastics pollution in lakes a serious concern. The inappropriate management of solid and liquid waste, which enters the lakes via various drains, surface runoff, direct sewage discharge into the lake, and atmospheric deposition, is mostly responsible for the introduction of MPs in these fragile ecosystems. The climate change can also lead to an increase in MPs pollution in freshwater lakes due to the heavy precipitation and surface runoff (Zhang et al., 2020), and the Himalayan regions are more susceptible to climate change and landslides due to the ongoing development. Tourism can also be one of the major factors affecting the abundance and distribution of MPs in the environment by direct disposal of plastic waste into the lakes, which thus gets broken down into smaller fragments forming MPs. Even after the filtration by sewage treatment plants, which cleans up 99.9% of MPs, still, some portion of the MPs enters the freshwater environment through the effluent (Carr et al., 2016).

1.5 Ecotoxicological effects of MPs on aquatic organisms and humans

The MPs present in the aquatic environment can be mistakenly consumed by the aquatic fauna as food particles, which can even lead to mortality due to the toxicity and affinity of MPs to other toxicants (Gopinath et al., 2020). Since the MPs have a large surface area per unit mass/volume, thus they can act as vectors (Retama et al., 2016), thus adsorbing various toxic chemicals or additives (Mason et al., 2016), which can enter the body of the organisms via water, food or sediments. MPs presence in various aquatic organisms has been studied, such as in fishes, mussels, barnacles, oysters, crustaceans, corals, and planktons, having negative impacts on the health of these organisms. Intake of MPs by these organisms can cause a reduction in feeding by accumulation and blockage of the alimentary canal (Cole et al., 2013), retarding growth, oxidative damage, and physical injuries such as blockages and internal abrasion (Wright et al., 2013; Rochman et al., 2013).

According to the study by Lamb et al. (2018), plastic debris in the marine environment causes light blockage, anoxia, production of toxins, pathogen intrusion, and damage, whereas chemical leaching and MPs concentration influence the number of macroinvertebrates and have ecotoxicological impacts on coral reef ecosystems. Particles smaller than 150 m may enter the gastrointestinal epithelium of the mammalian body as a result of constant exposure (Godoy et al., 2022), whereas particles of size 10µm can enter the organs and cellular membranes, as well as they can also cross the blood-brain barrier and placenta (Ragusa et al., 2021). It is seen in some fishes that the MPs can cause necrosis or damage to tumor tissues. When exposed to chronic PVC concentrations, the green mussel has been observed to have decreased respiration and clearance rates and production of byssus (Hariharan et al., 2020). Decreased root viability and growth have been observed on exposure to microbeads in the freshwater floating plant *Lemna minor*. These all make up an important part of the ecosystem, thus, the effect of MPs abundance will be a matter of concern.

1.6. SCOPE AND OBJECTIVES OF THE STUDY

1.6.1 Scope

Microplastic pollution is one of the emerging threats to the environment. MPs are found to be ubiquitous in the environment, and recent studies have discovered their presence in drinking water, tubewell water, and packaged food. Freshwater lakes can serve as the main sinks of MPs since they are semi-closed systems with a longer retention time frame. The areas influenced by tourist activities can show a higher accumulation of MPs. These lakes can serve as a source to introduce MPs into the marine environment. The aquatic fauna can also unintentionally consume the MPs present in lake water and sediment. These MPs can also act as a vector to transfer adsorbed chemical toxins on their surface, which, if consumed by aquatic organisms, can cause various harmful effects. Data is limited on freshwater lakes around the world. Nainital is one of the most famous tourist places in northern India, with Nainital Lake as an important place of tourist attraction. With this perspective, the present study concentrates on monitoring MPs in surface waters, surface sediments, tubewell water, and drinking water inside and around Nainital Lake, Uttarakhand.

1.6.2 Objectives

The present study focuses on the following objectives:

- To study the abundance and spatial distribution of microplastics in surface water and in the sediments of Lake Nainital, India.
- To investigate the morphological characteristics and polymer identification of microplastics in surface water and in the sediments of Lake Nainital, India.
- To evaluate the potential sources and distribution pathways for microplastics along the Nainital Lake.
- To suggest possible solutions and areas that need further research.

Chapter 2

REVIEW OF LITERATURE

2.1 Microplastics: A Disaster in Disguise

Microplastics were found for the first time in the environment in the early 1970s, in the surface water of the Sargasso Sea, when studies were conducted by Carpenter and Smith in 1972, and since then, microplastics have been found in every part of the globe. Larger plastic objects, or "Macroplastics," with a size of more than 2000 micrometers (µm), break into smaller fragments to produce secondary microplastics, which are further categorized into meso-size plastics (2000-200 µm), micro-size plastics (200-20 µm), and nano-size plastics (20-2 µm) (Bermúdez and Swarzenski, 2021). The breakdown of plastics takes place due to mechanical abrasion, biological breakdown, UV radiation, and atmospheric agencies (Singh and Sharma, 2008).

Primary microplastics are also present in the environment, which are produced by the industries and used as cosmetics products (Singh and Sharma, 2008), skin cleansers, or as 'exfoliating material' containing microbeads (Fendall and Sewell, 2009). Plastics are building up in practically every region of the world due to their slow decomposition rate and widespread use in almost every industry (Godoy et al., 2022). According to Geyer et al. (2017), plastic trash is one of the most prevalent and fastest-growing types of urban waste and is a significant global contaminant.

Microplastics are released into the environment due to poor management or improper disposal techniques. Due to the fact that all microplastics released into the environment are eventually gathered in the oceans, they can be thought of as the ultimate sinks for microplastics. According to Pastorino et al. (2020), around 32.9 million tons of plastic waste enters the oceans annually, accounting for only 10% of the plastic waste generated annually. Microplastics have been discovered in a variety of habitats, including sandy beaches, biota, near-shore sediments, and marine environments (Crump et al., 2020; Prestholdt and Kemp, 2020). Due to their lightweight and durability, these microplastics can travel long distances and even reach far-off locations via wind and water currents (Obbard and R.W., 2018).

According to an estimate by Eriksen et al. (2014), around 5 trillion microplastics are floating in the sea, having a total weight of 250.000 tons worldwide. The microplastics resemble tiny dirt particles and can be ingested by plankton and other aquatic fauna. The consumption of microplastics may expose aquatic organisms to dangerous toxins. (Zhang et al., 2016). Microplastics can also get into the aquatic food chain and obstruct an organism's ability to grow by blocking its digestive tract. Surface runoff, improper disposal, factory spillage, and wastewater discharge are significant contributors to microplastic pollution (Gasperi et al., 2014; Zbyszewski et al., 2014).

2.2 Abundance of Microplastics in the Environment

Microplastics have been discovered in a variety of habitats, including the atmosphere, sediments, beaches, and even in the remote areas.

2.2.1 Marine environment

Vianello et al. (2013) examined the distribution and abundance of MPs in the coastal area of the Mediterranean Region, along the North-Eastern Italian Coasts, the Lagoon of Venice. The presence of MPs was confirmed in all the ten sediment samples, indicating their widespread distribution throughout the Lagoon. The abundance was estimated to be around 2175-672 MPs Kg^{-1} d.w. (dry weight), indicating the higher concentrations in the landward site. The dominant types were PE and PP, i.e., 82%, with the most frequent size of MPs in the range of 30-500 µm. Dekiff et al. (2014) studied the distribution of Small Potential Microplastics (SPM) of size <1mm and their correlation with VPD on a 500 m stretch of the North Sea Island of Norderney. The mean SPM at 3 sampling sites was found to be 1.7, 1.3, and 2.3 particles Kg^{-1}, and the types were identified as PP, PE, PET, PVC, PS, and the organic plastic additives were found to be benzophenone, 1,2-benzenedicarboxylic acid, dimethyl phthalate, diethyl hexyl phthalate, dibutyl phthalate, diethyl phthalate, phenol, and 2,4-di-tert-butylphenol. The particles had a homogeneous distribution, and no correlation between MPs and VPD was discovered.

According to the study conducted by Karthik et al. (2018), on the 25 sandy beaches along the Tamil Nadu coast to assess the amount of plastic waste on the state’s beaches, the samples were collected from the high tide line and low tide line. The results show the dominance of plastic fragments (47-50%), fibers/lines (24-27%), and the least foam (10-19%), out of which PE, PP, and PS were the dominant types of microplastics. The fish samples were collected from the coastal waters, and their gut analysis shows the presence of MPs in 10.1% of the samples. Microplastics were examined by Robin et al. (2019) in coastal waters (14 places), beach sediments (22 locations), and marine fishes (11 locations) from Kerala, the southwest coast of India. The results demonstrated the mean abundance of MPs observed in coastal water (1.25 0.88 particles m^{-3}) and in beach sediments (40.7 33.2 particles m^{-2}), with higher concentrations in the southern coast of the state. Fragments, fiber, and foam were the dominant MP types. On the basis of FTIR spectroscopy data, PE and PP dominated the marine environment. The presence of 22 MPs was observed in the digestive tracts of 15 fish, with PE accounting for 38.46%, followed by cellulose (CE=23.08%), rayon (RY=15.38%), polyester (PL=15.38%), and propylene (PP =7.69%). The MPs contained a number of potentially hazardous chemicals, including heavy metals, metalloids, and other elements.

The prevalence and features of microplastic pollution in the Nordic Seas were studied by Jiang et al. (2020). In the region impacted by the East Greenland Current, MP abundance was determined to be 1.19±0.28 items L^{-1}, with fibers (76.1%), transparent (76.2%), and small MPs (0.1-0.5 mm, 48.1%) being the most prevalent forms. The MPs abundance in the Greenland Sea Gyre-affected cold basin was 2.43 0.84 items L^{-1}, with the dominating types being fiber (87.2%), transparent (87.6%), and tiny MPs (63.9%). According to SEM findings, MPs have heavy metals adsorb onto their surfaces as well as multiple weathering and abrasion sites on their surface. According to FTIR data, PL and PE were dominant in the Nordic Sea Beaches. Dutta et al. (2022), investigated the MPs contamination in the sediments and water columns of three chosen Mumbai beaches (Aksa, Versova, and Girgaon Chowpatty), providing information on the morphological features and spatiotemporal variance. All of the beaches had significant MP concentrations in the summer. This study also found spatial variation, with Versova and Girgaon Chowpatty beaches having a higher abundance than Aksa Beach. The average MPs in marine sediments and seawater columns were 204±110 particles Kg^{-1} and 103± 60 particles L^{-1}. Beads were the most abundant in both categories, while fibers were the least abundant. The majority of the particles that were seen belonged to the 0.45 to 500 µm size range.

2.2.2 Beaches

Stolte et al. (2015), conducted a study to examine the contamination with MP particles and fibers on the beaches along the German Baltic Coast. From March to July 2014, sediment samples were collected, and seasonal fluctuations were observed. The results indicated the presence of MPs, i.e., 0-7 particles Kg^{-1} and 2-11 fibers Kg^{-1} dry sediment. The sources with the highest concentrations were discovered to be industrial production locations, fishing activity, and city discharges. The average concentration and features of macroplastics (> 2.5 cm), mesoplastics (5 mm - 2.5 cm), and microplastics (5 mm) were examined by Jeyasanta et al. (2020) on eight sandy beaches near Tuticorin, Tamil Nadu. The mean abundance of macroplastics (1.38 ± 78 to 6.16 ± 94 items m^{-2}), mesoplastics (2 ± 0.8 to 17 ± 0.11 items m^{-2}), and microplastics (25 ± 1.58 to 83 ± 49 items m^{-2}) were estimated, of which PE is the most predominant polymer followed by PE, PP, PET, NY, PS, and PVC. There is a link between fishing activity intensity and the concentrations of macro- ($p = 0.02$) and microplastics ($p = 0.03$) at Sites 1, 2, 3, 5, and 8, and also there is a link between the amount of recreational activity and the amounts of meso- ($p = 0.02$) and microplastics ($p = 0.01$) at Sites 4, 6, and 7.

The abundance of buried MPs in sand profile and pellet pollution index at Sarakkuwa beach, west coast of Sri Lanka, was studied by Sewwandi et al. (2022), due to the receival of plastic nurdles and debris from the MV X-Press Pearl ship disaster in May 2021. Analyzing sand samples taken from 7 sites between March 2020 and October 2021, it was discovered that they were polluted with pyrolyzed LDPE fragments and nurdles, with a peak abundance of 13.3702 particles Kg^{-1} and LDPE fragments ranging in size from 1mm to 500 µm down to a depth of 2.0 m. Mo and Cr were found in significant amounts in the sand samples taken in 2021, indicating that the beach is severely contaminated by debris, partially pyrolyzed microplastics, and poisonous substances left behind from the ship disaster. Markic et al. (2023) investigated the microplastic contamination of intertidal and subtidal sediments in the Vava'u archipelago, Tonga. The MPs were discovered in concentrations of 23.5±1.9 and 15.0±1.9 particles L^{-1} of sediment in the intertidal and subtidal sediments, respectively. This demonstrates the dominance of fibers in both intertidal (85%) and subtidal (62%) sediments.

2.2.3 Rivers

In the Rhine-Main region of Germany, Klein et al. (2015) conducted an analysis of the occurrence of MPs in river beach sediments from the Rhine and Main rivers. The sample sites included places close to nature reserves as well as the beach sediment of two major European rivers, the Rhine and the Main, with diverse populations and industrial influences. Approximately 4000 particles Kg^{-1} of MPs <5 mm was found in the sediments. Results from IR spectroscopy revealed that PE, PP, and PS were present in over 75% of the samples. Pellets contained in the samples, which were isolated from shore sediment samples of both rivers, demonstrate short-distance transport by the tributary to the mainstream. This study highlights the significance of rivers serving as vectors for MP transmission to the oceans. Microplastics in the surface sediments from the Beijiang River littoral zone were evaluated by Wang et al. (2017) for their abundance, composition, surface texture, and interactions with heavy metals. According to the findings, there are between 178±69 and 544±107 items Kg^{-1} of sediment. µFTIR detected chemical deterioration, while SEM pictures revealed pits, fractures, flakes, and adhering particles. EDS spectra showed the various metal elemental types (Ni, Cd, Pb, Cu, Zn, and Ti) on the various surface sites of each individual microplastic, demonstrating that some of the metals transported by microplastics were not intrinsic but were taken from the surroundings.

Buwono et al. (2021) examined the abundance and type of MPs present in the four locations from January to March 2020 in the Brantas River, the longest river in East Java. The relationship between the physiochemical properties of water and MPs was also studied. The overall abundance ranged from 133 to 5467 particles m^{-3}. The ANOVA demonstrated that there are differences in sample abundance between the locations ($p=0.05$). According to Tukey's test, MPs varied between sites; the downstream location dominated in fragments (68%–78% of the total), whereas the upstream location dominated in fibers (39%–47% of the total). Temperature, turbidity, TSS, and BOD are the main physical and chemical factors contributing to pollution at this site.

Microplastic pollution in river shore sediment of the Indian Himalayas, including the Brahmaputra River and the Indus River, was studied by Tsering et al. (2021). The MPs of size 20–150 µm were more abundant (531–3485 MP Kg^{-1} in the Brahmaputra River and 525–1752 MP Kg^{-1} in the Indus River) than Ms in the size range of 150 µm and 5 mm (20–240 MP Kg^{-1} in the Brahmaputra River and 60–340 MP Kg^{-1} in the Indus River). All sediment samples confirmed the presence of MPs, in which Fragmented MPs were dominant in the river shore sediment of the Indian Himalayas.

Ayyamperumal et al. (2022) investigated the MPs pollution in channel bed sediments from 15 sites in the urban river catchments of Coimbatore, categorized by kind, shape, size, and color. It was discovered that the dried sediment abundance near the river mouth ranged from 500 to 6500 items m^{-3}, with green, blue, white, transparent, and other colors predominating among a variety of various shapes, colors, and compositions. The types of MPs that are examined using ATR-FTIR include PP, PET, PS, LDPE, and PVAC.

The presence and spread of microplastic contamination in the Torghabeh River sediments in Khorasan Razavi, Iran, were examined by Bonyadi et al. (2022). Samples of the river's sediment were taken at four different locations and were categorized by type, shape, and color categories. In 100g of dry sediments, there were 8±2.82 microplastic particles on average. In river sediments, filaments and fragments made up the majority of the microplastics. 32 different polymers were found in the sediments and isolated. Raman spectroscopy results showed that, among PL, PE, and other polymers, PS was the one with the highest abundance.

The presence of MPs in water and sediment samples from the Plankenburg River in the Western Cape of South Africa was examined by Apetogbor et al. (2023). Four seasons of sampling were done: spring, summer, autumn, and winter. In the surface water samples, the seasonal distribution of MPs varied between sites. However, the proportion of MPs was highest in spring samples (5.13±6.62 MP L^{-1}) and lowest in autumn samples (1.52±2.54 MP L^{-1}). In spring, MPs were found in sediment samples (1587.50±599.32 MP Kg^{-1}). With a size range of 500-1000 µm at the various sites, fibers were the most prevalent microplastic particle type. The infrared spectroscopic examination showed that PE was the most prevalent form of polymer**.**

2.2.4 Topsoil

In Coimbra City, Portugal, Leitão et al. (2023) assessed the microplastic contamination in urban soils from artificial and natural land usage. The microplastic concentration ranged from 5×10^3 to 571×10^3 particles Kg^{-1}, with a mean of 106×10^3 particles Kg^{-1}. The forest had the lowest concentration of microplastics (55×10^3 particle Kg^{-1}), whereas the green park had the highest concentration (158×10^3 particle Kg^{-1}). The artificial places with the highest concentrations of microplastics were the dump (126×10^3 particle Kg^{-1}), industrial (127×10^3 particle Kg^{-1}), and landfill (150×10^3 particle Kg^{-1}). The predominant polymers were PP and PE, followed by PVC and rubber, and the most common diameters ranged from 50 to 250 µm. The results show that, in urban areas, natural places are more likely than artificial spaces to contain greater levels of microplastics.

2.2.5 Glaciers

Ambrosini et al. (2019) discovered the presence of MPs in the terrestrial glacier environment for the first time in Forni Glacier, Italian Alps. The observed MPs contamination was found to be 74.4±28.3 items Kg^{-1} d.w. of sediment, dominated by

Polyesters, followed by PA, PE, and PP. According to an estimate, the entire ablation region of the Glacier has 131–162 million plastic items. Anthropogenic activities result in the direct discharge of MPs or the possibility of wind transport at high altitudes. Kelly et al. (2020), assessed the presence of microplastics in the East Antarctic Sea with one ice core sample from coastal land-fast sea ice. The µFTIR spectroscopy revealed the presence of 96 MPs, with an average of 11.71 particles L^{-1}. PE, PP, and PA were discovered to be the three most prevalent MPs. It was discovered that the MP concentrations in the sea ice were connected to chlorophyll a, demonstrating the ability of living biomass to transmit MPs into the sea ice. According to the study, sea ice can serve as a significant sink for MPs debris in the Southern Ocean, which may have an impact on the food webs and biogeochemistry of the Southern Ocean.

Chubarenko et al. (2022), in the early spring studied the first-year sea ice cores (38–41 cm thick) in a small, densely inhabited bay of the Sea of Japan. Layer by layer, excluding the surface, two ice cores were analyzed for the presence of MPs: one using FTIR for 25-300 µm (SMPs), and the other using visual Raman identification for 300-5000 µm particles (LMPs). The bulk mean abundance of MPs (25–5000µm) was found to be 428 items L^{-1} of meltwater, with fibers accounting for 19% of SMPs and 59% of LMPs. The estimated integral mean mass of MPs was 34.6 mg L^{-1}, with 99.6% of the mass coming from LMP fragments. Large fiber (>300 µm) counts and ice salinity shows a high positive association, according to multivariate statistical analysis.

2.2.6 Rain

By examining MPs that had been left behind by rain in Shiraz City, southwest Iran, after a particularly heavy monsoon event on July 18, 2021, Abbasi (2021) evaluated the presence, features, length of washout, and likely sources of MPs. According to the data, the wet deposition in total over the course of 30 minutes was 260 MPs m^{-2}, with the majority of those MPs, particularly the larger ones (ranging from 250 to >1000 µm), deposited in the first ten minutes. The aerodynamic equivalent fiber diameters ranged from 8 to 180 µm. MPs were discovered to be dominated by PE and PS. The source of the MPs, along with satellite imagery, HYSPLIT modeling, and using micro rubbers (MRs) as an indicator, suggests that MPs are more likely to have a local (or urban) origin, with some of the small fibrous ones being brought from the Persian Gulf and/or remote regions. MPs showed varying degrees of mechanical weathering and photo-oxidation.

2.2.7 Aquatic Fauna

Cole et al. (2013) demonstrated the consumption of MPs by common zooplankton in the northeast Atlantic and investigated the feeding rate to find out the effect of plastic debris on rates of copepod ingestion of algae. The intake capacity of 13 different taxa was determined using fluorescence and CARS microscopy, which ranged from 1.7 to 30.6 µm, depending on the taxa, stage of life, and bead size. The egested faeces were discovered to be heavily packed with MPs, and MPs were also observed adhering to the exposed zooplankton's exterior carapace and appendages. The presence of 7.3 µm MPs (>4000 mL^{-1}) in the exposed copepod *Centropages typicus* drastically reduced algal consumption.

Setälä et al. (2014) studied the potential of different zooplankton present in the Baltic Sea to ingest the plastics. Mysid shrimps, copepods, cladocerans, rotifers, polychaete larvae, and ciliates were fed with 10 m fluorescent PS microspheres. The results showed intake by all organisms, and the highest was consumed by pelagic polychaete larvae, Marenzelleria spp., whereas copepod Eurytemora affinis and the mysid shrimp Neomysis integer showed egestion within the 12h. These experimental zooplanktons were fed to mysid shrimps, and the ingestion was detected after a 3h incubation period. This study demonstrated the potential of plastic microparticle transmission from one trophic level (mesozooplankton) to a higher level (macrozooplankton).

Nelms et al. (2018) examined the full digestive tracts of the wild-caught Atlantic mackerel (*Scomber scombrus*) that the grey seals (*Halichoerus grypus*) are fed upon in order to study the trophic transmission of MPs in organisms. In half of the scat subsamples (48%; n=15) and a third of fish (32%; n=10), around 1-4 MPs were found which were mostly black, colorless, red, and blue in color. FTIR spectroscopy confirmed the presence of Ethylene and Propylene in both the samples. The crucial survival behaviors of contacting, examining, and choosing an ideal shell in common European hermit crabs (*Pagurus bernhardus*) were examined by Crump et al. (2020). In the 64 samples that were examined over the course of the five-day study, 35 samples containing PE revealed crabs to have impaired shell selection; these crabs were less likely than controls (n=29) to make contact with or enter ideal shells. According to the results, microplastics affect cognition (the gathering and processing of information) and interfere with a crucial survival behavior in hermit crabs.

The effects and accumulation behavior of weathered Polyethylene (wPE) microplastics in *Perna viridis* were studied by Hariharan et al. (2020). In a 30-day experiment, the organisms were exposed to 3 different concentrations of wPE, which then was followed by a one-week depurination phase. According to the study, feeding decreased in organisms exposed to higher levels (3µg L^{-1}), and wPE accumulated in their intestines, but no mortality was detected. Additionally, it was shown that ingestion had an impact on internal organs, growth, and reproduction, depending on the size of the wPE particles consumed. Overall, the study found the intestine to be the most sensitive organ to the effects of wPE, followed by gills, adductor muscles, and foot tissue.

2.3 MPs in Freshwater Lakes: Global Abundance and Distribution

Eriksen et al. (2013) examined the plastic debris present in the Laurentian Great Lakes, United States. Using a 333 m mesh manta trawl, 21 neuston samples were taken in July 2012, and the average abundance was reported to be 43,000 MP particles Km^{-2}. Maximum MPs, about 466,000, were present in the downstream position of both cities, which was more than all the stations put together. The majority of the MPs discovered were multi-colored spheres that resembled the microbeads used in the products. In Lake Hovsgol, a large, remote alpine lake in Mongolia, Free et al. (2014) assessed the quantity, distribution, and composition of pelagic microplastic pollution. In comparison to the more developed Lakes Huron and Superior, i.e., Laurentian Great Lakes, Lake Hovsgol has a higher average MPs density, measuring 20,264 particles Km^{-2}. The most prevalent microplastic kinds were fragments and films; plastic microbeads and pellets were not found. The majority of the coastline trash was made up of household plastics, which mostly included plastic bags, bottles, and fishing gear. The results of this study show that low-density populations can severely contaminate freshwater systems with household plastics if effective waste management is not implemented.

Zhang et al. (2016) studied the MPs (5mm) in the lakeside sediments of four lakes located in the Siling Co basin, northern Tibetan. In six of the seven test locations, microplastics were found in abundance ranging from 8±14 to 563±1219 items m^{-2}. The high concentration of microplastics found in this isolated location may have been caused by riverine input. Morphological characteristics imply that microplastics come from the decomposition of frequently used plastic goods. Laser Raman spectroscopy revealed that the MPs detected were PE, PP, PS, PET, and PVC. Using a saturated NaCl flotation technique, Toumi et al. (2019) identified MPs in the surface sediment of seven streams in the Bizerte lagoon (Northern Tunisia). The results revealed that MPs were present in all sediment samples. The Jedara stream had the highest MP abundance (6920±395.98 items Kg^{-1} dry weight), whereas the Khima stream had the lowest mean value (2340±227.15 items Kg^{-1} dry weight). The secondary MPs present in the samples were fibers, followed by films and fragments. The predominating hues were: black > clear > white > red > blue > green > yellow for fibers, white > blue > black > red for fragments, and red > white > clear > green > blue >black for films. FTIR examination showed that PP and PE were the most prevalent polymers.

Pastorino et al. (2020) investigated the levels of plastic (>500 µm) and microplastic (10-5000 µm) in the snow at the end of the winter season (April 2020), in water, sediment, as well as in biological samples, collected monthly (June-October 2019) during the ice-free season from the Dimon Lake, a high-mountain lake in the Carnic Alps, northeast Italy. Chironomids (Diptera, Chironomidae; n = 150) and the stomach contents of Cottus gobio (n = 40) comprised the biological samples. Plastic and microplastics larger than 10 µm were not found in the water, sediment, or biological samples; however, PET microplastics were present in the snow samples but in very small quantities (0.11±0.19 L^{-1}).

Velasco et al. (2020) examined the existence and abundance of MPs and fibers in a distant, alpine, and abandoned lake in Switzerland (Sassolo). Both the water column and the sediments were examined in this investigation. In the water column, an average of 2.6 MPs and 4.4 fibers L^{-1} were found. However, the results of the sediment tests showed that there were far more fibers present than plastic microparticles (514 fibers and 33 MPs Kg^{-1}). PE and PP were the most prevalent kinds of MPs found in the samples. Malygina et al. (2021) conducted an analysis of the abundance, composition, and spatial distribution of MPs in six lakes in southern Siberia, including the West Siberian Plain and the Altai mountains. All of the lakes under study included MPs, and their concentrations ranged from 4 to 26 MPs L^{-1}. South Siberian lakes showed moderate MPs concentrations when compared to other inland lakes. Films and fragments were dominant among the MPs, with sizes ranging from 31 to 60 nm. The MP's sources depend on surrounding human activity (fishing, transport, landfilling). As a result, even in remote lakes, sufficiently high quantities of MPs were observed.

To identify the local parameters that regulate their distribution, Godoy et al. (2022) conducted a first-ever analysis of the abundance of microplastics on the surface of 35 glacier lakes in the Sierra Nevada National Park, Southern Spain. The results indicate that microplastics were widespread in most lakes, with a maximum abundance of 21.3 particles L^{-1}, which is comparable to some of the lakes with the highest levels of microplastic pollution worldwide. The most common shapes were fragments (59.7%), followed by fibers (38.8%) and relatively few spheres (1.5%). All size fractions of microplastics were detected, although the number of particles <45μm was higher, which justifies the usage of low pore-size filters to avoid underestimating the presence of microplastics. In the Nam Co Basin, Tibetan Plateau, Dong, et al. (2023) investigated the properties of microplastics in lake water, glacier runoff, and non-glacial runoff. The findings indicate that fibers and films predominated in the samples. In the glacier runoff, a larger percentage (37%) of light-weight PP and small-size MPs (50-300 m, ~30%) were identified. The monsoon season's air fallout was calculated to be 3.3 tons for microplastic loading in lakes, although the contributions from glacial and non-glacial runoff were quite small (~41 kg and ~522 Kg, respectively). The atmospheric deposition for the microplastic loading in glaciers was ~500 Kg/year, while the output from glacial melting only accounted for 8% of the total atmospheric input.

2.4 Microplastics in Freshwater Lakes in India: Their Prominence and Dispersion

MPs have been discovered in various freshwater lakes in India at different locations, some of them are present in urban areas, and some are at high altitudes, affected by anthropogenic activities. The comparison of MPs among the freshwater lakes of India is shown in **Table 1**.

Table 1: Comparison of abundance, shapes, and polymers of MPs present in different freshwater lakes in India.

Samples	Location	Abundance	Shapes	Polymers	References
Sediment	Vembanad Lake, Kerela	252.80 ± 25.76 particles m^{-2}		LDPE	Sruthy and Ramasamy (2016)
Sediment and Water	Red Hills Lake, Chennai	Sediment= 27 particles Kg^{-1} Water=5.9 particles L^{-1}	Fibers (37.9%), fragments (27%), films (24%), and pellets (11.1%)	HDPE, LDPE, PP, and PS	Gopinath et al. (2020)

Samples	**Location**	**Abundance**	**Shapes**	**Polymers**	**References**
Surface Water and Sediment	Veeranam Lake, Tamil Nadu	Surface water= 28 items Km^{-2} Sediment= 309 items kg^{-1}	Fragments > Foam > Pellets	NY (39%), PE (23%), PS (19%), PP (15%), and PVC (4%).	Bharath et al. (2020)
Water and Sediment	Freshwater Lake system, Lesser Himalayas	Water= 02–64 particles L^{-1} Sediment=15–632 particles kg^{-1} dw	Fibers and Fragments	PE and PS	Ajay et al. (2021)
Shore Sediment	Pangong Lake, Tsomoriri Lake and Tsokar Lake, Ladakh	Pangong Lake= 160-1000 MP Kg^{-1} dw Tsomoriri Lake= 960–3800 MP Kg^{-1} dw Tsokar Lake= 160–1000 MP Kg^{-1} dw			Tsering et al. (2022)
Sediment	Anchar Lake, Kashmir Valley, Northern Himalayas	606 ± 360 MP Kg^{-1} dw	Fibers (91%), fragments/Films (8%), and Pellets (1%)	PA (96%), PET (1.4%), PS (1.4%), PVC (0.9%), PP (0.7%).	Neelavannan et al. (2022)
Surface Water, surface and Core Sediment	Kodaikanal Lake, Tamil Nadu	Surface water= 24.42 ± 3.22 items L^{-1} Surface sediment= 28.31 ± 5.29 itemsKg^{-1} Core Sediment= 25.91 ± 7.11 items Kg^{-1}	Fibers and Fragments	PE and PP	Laju et al. (2022)
Surface Water and Sediments	Rewalsar Lake, Northwest Himalayas	Surface water= 13-238 particles L^{-1} Sediment= 750-3020 Particles Kg^{-1} dw	Pellets and Fragments	PS, PE, PP	Bulbul et al. (2023)
Surface Water	Ousudu Lake, Puducherry	0.0039 particles m^{-2}	Fiber	PE	Varshini et al. (2021)

Chapter 3

MATERIALS AND METHODS

3.1 Study Area

Nainital town (29^0 24’19” N, 79^0 25”46” E), also known as ‘The Lake Town of Uttarakhand/ the Himalayan Lake Town, located in the foothills of Kumaon Himalayas, is one of the most renowned hill stations in the Uttarakhand state of northern India (**Fig. 3.1**). It lies in the Shivalik range at an elevation of 1,934 meters above sea level, covering an area of 11.89 Km^2. Nainital is famous for its scenic beauty, pleasant weather, and recreational activities, attracting a large number of tourists from around the globe. Nainital has a temperate climate; in summers, the temperature ranges between 10ºC and 25ºC, whereas in winters, the temperature ranges between 0ºC and 15ºC. The average rainfall in the town is around 110 cm.

Fig. 3.1 Study site- Nainital Lake, Uttarakhand, India

The town has 15 wards with a population of 41,377 (Nainital District Population Census 2011) (**Fig. 3.2** and **Fig. 3.3**). The town’s floating population goes from 20,000 to 50,000 per day during the peak season. The Nainital Lake, or Naini Lake, is a crescent-shaped, warm monomictic, natural freshwater lake situated in the heart of the city, surrounded by the panoramic seven hills (A Report on Naini Lake, 2017), is the main attraction point of Nainital town.

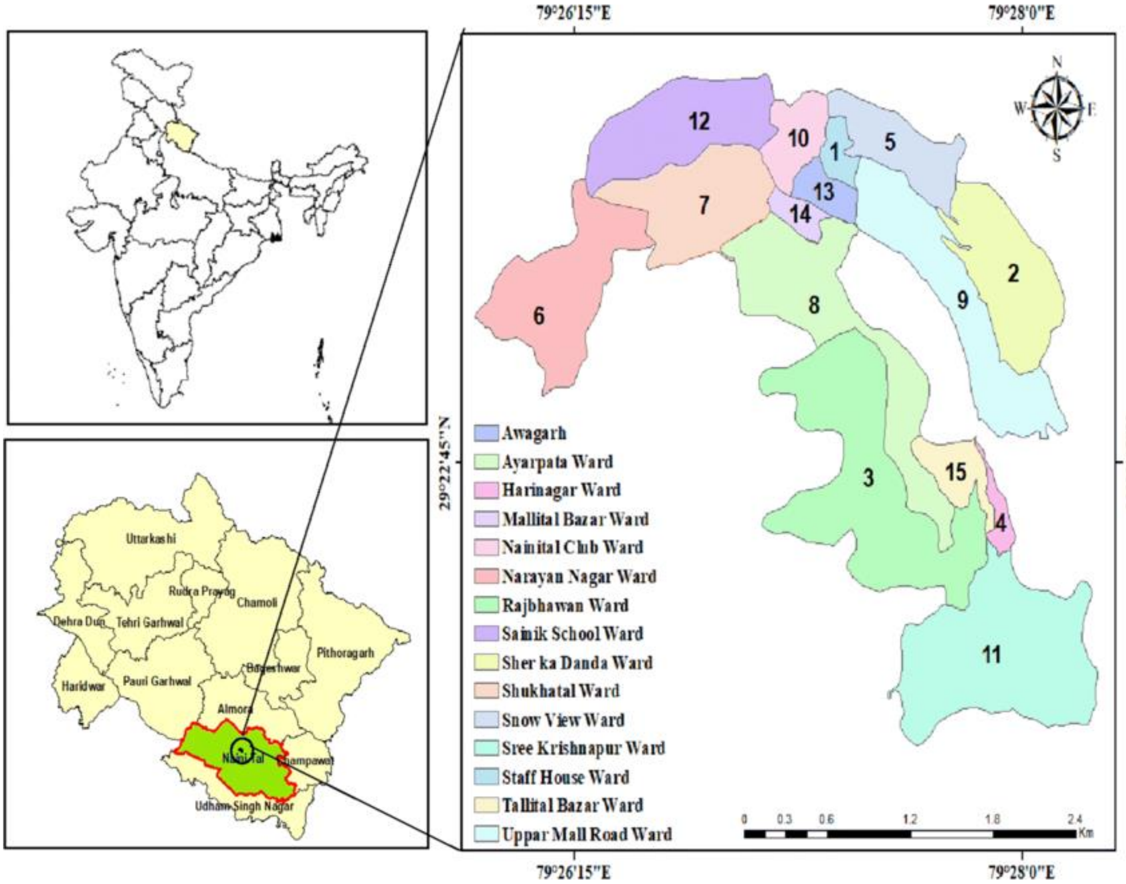


Fig. 3.2. Ward map of Nainital town, located around the Nainital Lake (Source: Chauhan et al., 2021)

The lake has a tectonic origin and covers an area of 0.49 Km^2, with maximum and mean depths of 27.3m and 16.5m. The lake is divided into two sub-basins by a 100m wide transverse underwater ridge, into Tallital (lower) and Mallital (upper) basins, that is located 7m below the surface (Jain et al., 2007), and because of the presence of the ridge, the water of two sides does not mix during thermal stratification (Rawat, 1987). Nainital Lake is the primary source of water for the Nainital town. The water supply of the town is based on the pumping system from the lake. The bore wells and infiltration well, situated at the banks of the lake, are used for taking up the water. The tubewells account for the water supply for 93% of the population of the town, whereas the surface source accounts for 7% of the water supply (A Report on Naini Lake, 2017). The ephemeral Sukhatal Lake replenishes the

Nainital Lake, and water travels via the fault zone to the Pardadhara Spring before arriving at the Nainital Lake (EERC, 2002).

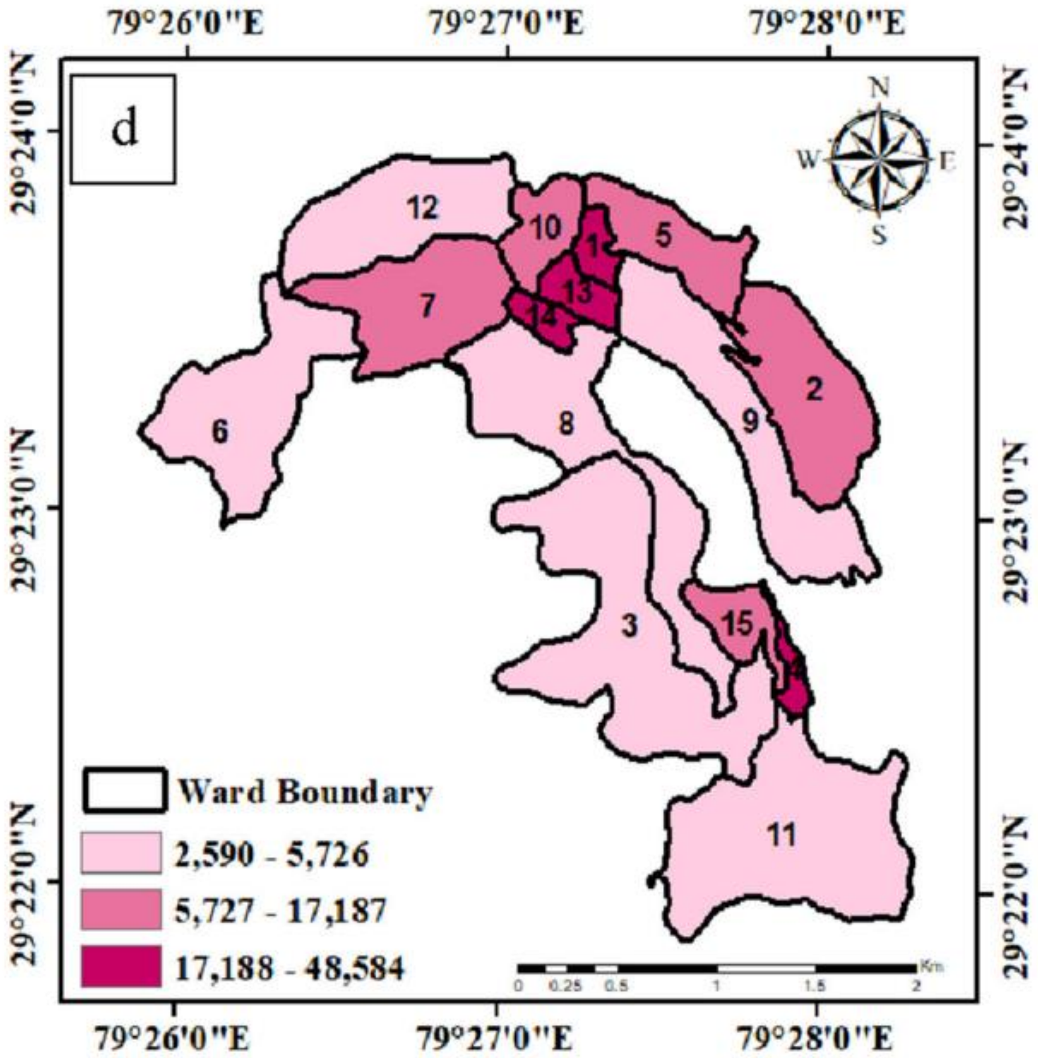


Fig. 3.3 Ward-Wise Population Density of Nainital Town (Source: Chauhan et al., 2021)

The water enters the lake through springs, rainwater, and inlet drains, which act as the main source of polluted sludge and silt into the lake (Purushothaman et al., 2012). The lake is fed by 44 drains, out of which 2 are perennial. The Naina Devi Temple drain, or Bara Nala, is the main drain, which contains the water from the drainage in residential areas and springs waters from the western end. The Bara Nala and one more drain at the Mallital bus stand are the perennial drains. The Naina Devi drains receive large amounts of water from the Pardadhara spring, located at the Nainital fault (EERC, 2002). The excess water from the lake is released through the sluice gates (Pathak et al., 2021), which are present at the south end of the lake, through which the water flows down the hills as the ‘Baliya River’ (**Fig. 3.4**). The increase in the population in recent years, tourism, and construction increases the pressure on the lake. The increasing construction activities and tourism is affecting the quality of lake water. Also, the direct discharge of untreated wastewater, silt deposition due to the landslides in the lake periphery, and disposal of solid waste have led to the degradation of lake water quality. The drains carrying water from the nearby hills meet directly with the lake, thus releasing toxic material, like heavy metals, into the lake, which then settles down at the lake bottom. The sewage and domestic waste entering the lake contains organic material, which creates anoxic conditions in the lake, in turn increasing the Biochemical oxygen demand (BOD) of the lake. To decrease the BOD concentration in the lake, the government has set up 2 aeration units, which release the compressed air at the bottom of the lake, with around 310kPa pressure.

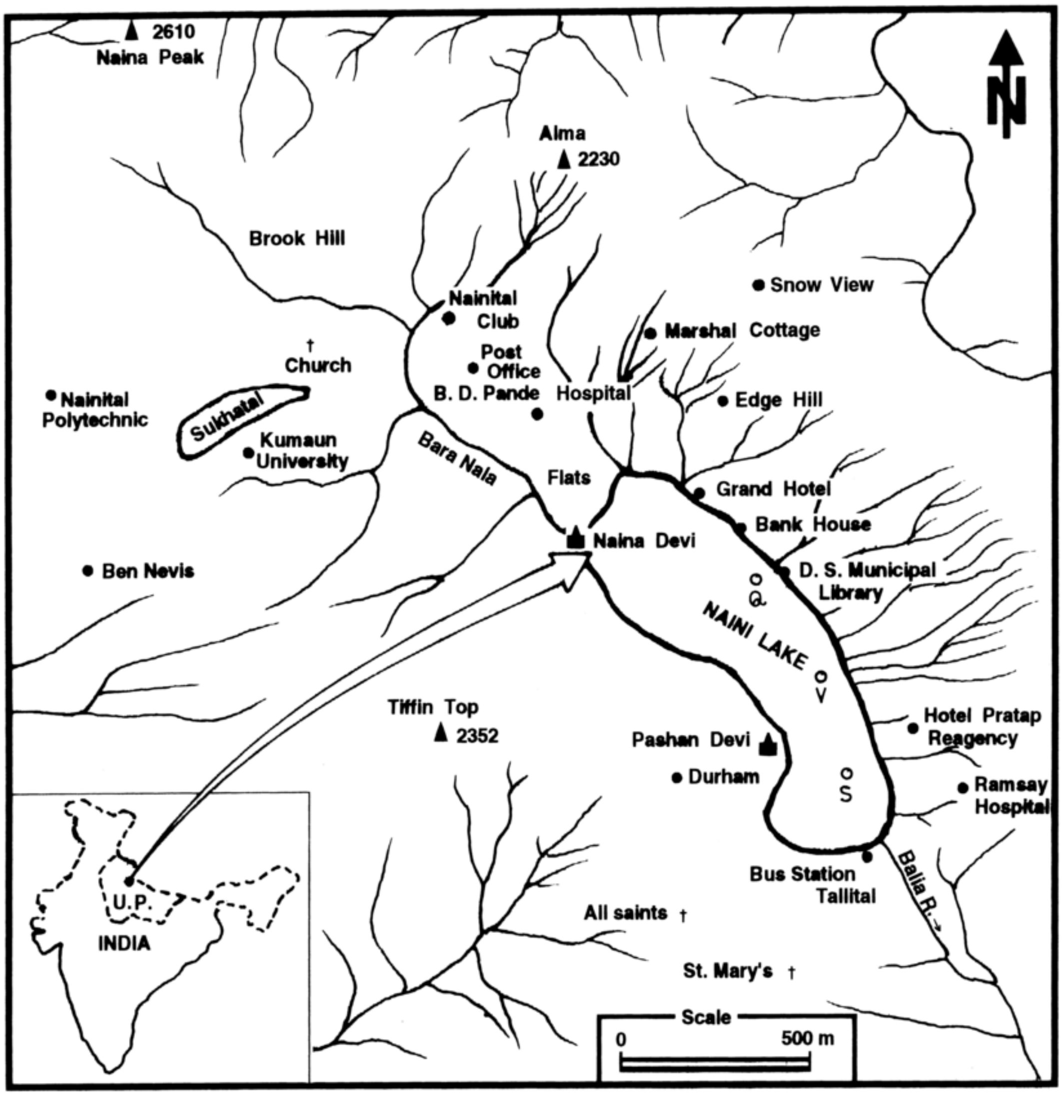


Fig. 3.4 Drainage map of Nainital town (Source: Kumar et al., 1999)

According to Nainital Municipal Council (NMC) Solid Waste Management (SWM) Cell, the total solid waste generated in the Nainital town is around 15 Metric Ton (MT) per day, which contains around 8-8.5 MT of dry waste and 6.5-7 MT of wet waste. As of 2023, there are 15 wards in the city, and the waste collected per day by NMC is around 1 MT. The monthly production of waste goes up to 4500 MT in the off-season. This waste comes up to 16-17 MT per day in the tourist season. Solid waste consists mainly of tourist and household-generated waste such as organic, plastics, paper, glass, textiles, etc. Plastic waste generally consists of PET bottles, food containers, carry bags, packets, cups, etc., which are mostly generated by tourists. As per NMC, the segregation of solid waste produced is done at small scales in schools and hotels. For the segregation and recycling purposes for the waste produced by the complete town, the solid waste is collected and sent daily to the Solid Waste Management Plant, set up in Haldwani, District Nainital, as there is no such facility to segregate waste in the town itself. The collection of Solid Waste from the lake is done manually by the workers using nets. Around 25-27 self-help groups are working on the source segregation of solid waste. Several self-help groups are working in the city to increase awareness and for source segregation of the waste in the Nainital town.

3.2 Sampling Sites

The sampling was carried out in February 2023, and based on the effects of anthropogenic activities on the high-altitude mountain lake, the tourist hotspots, and the residential areas were selected in the Nainital town for the collection of samples. A total of 16 sites were selected in and near the catchment area of Nainital Lake for the sampling. Water (13 samples) and sediment (7 samples) were collected from the selected locations marked as S1-S10. The geographical coordinates of each location were recorded using the Global Positioning System (GPS) (**Fig. 3.5**). The surface water samples and sediment samples from the lake, tubewell water, tap water, drainage water, and sediment were collected. A total of 6 sites were identified as hotspot areas (HS1-HS6), and water, sediment, and plastic wastes were also collected from the locations on the basis of residential areas and tourist activities as shown in **Table 2**.

Table 2: Activities going around different locations from where the samples were collected

Sl. No.	Latitude	Longitude	Station Name	Description
1	29.39113	79.45267	HS1	Residential area, market
2	29.38989	79.45491	HS2	Water purification plant
3	29.38516	79.46272	HS3	Tourism
4	29.38086	79.45997	HS4	Residential area
5	29.38431	79.45974	HS5	Temple
6	29.38831	79.45479	HS6	Market, Temple
7	29.39004	79.45529	S1	Temple, Boating, Market
8	29.39058	79.45751	S2	Boating
9	29.38518	79.46248	S3	Boating, Hotels
10	29.38253	79.46347	S4	Boating, Hotels
11	29.38073	79.46363	S5	Boating, Hotels
12	29.38008	79.46156	S6	Residential area
13	29.38086	79.45997	S7	Residential area
14	29.38162	79.46029	S8	Residential area
15	29.38384	79.46039	S9	Temple, Landslide area
16	29.38543	79.45864	S10	Residential area

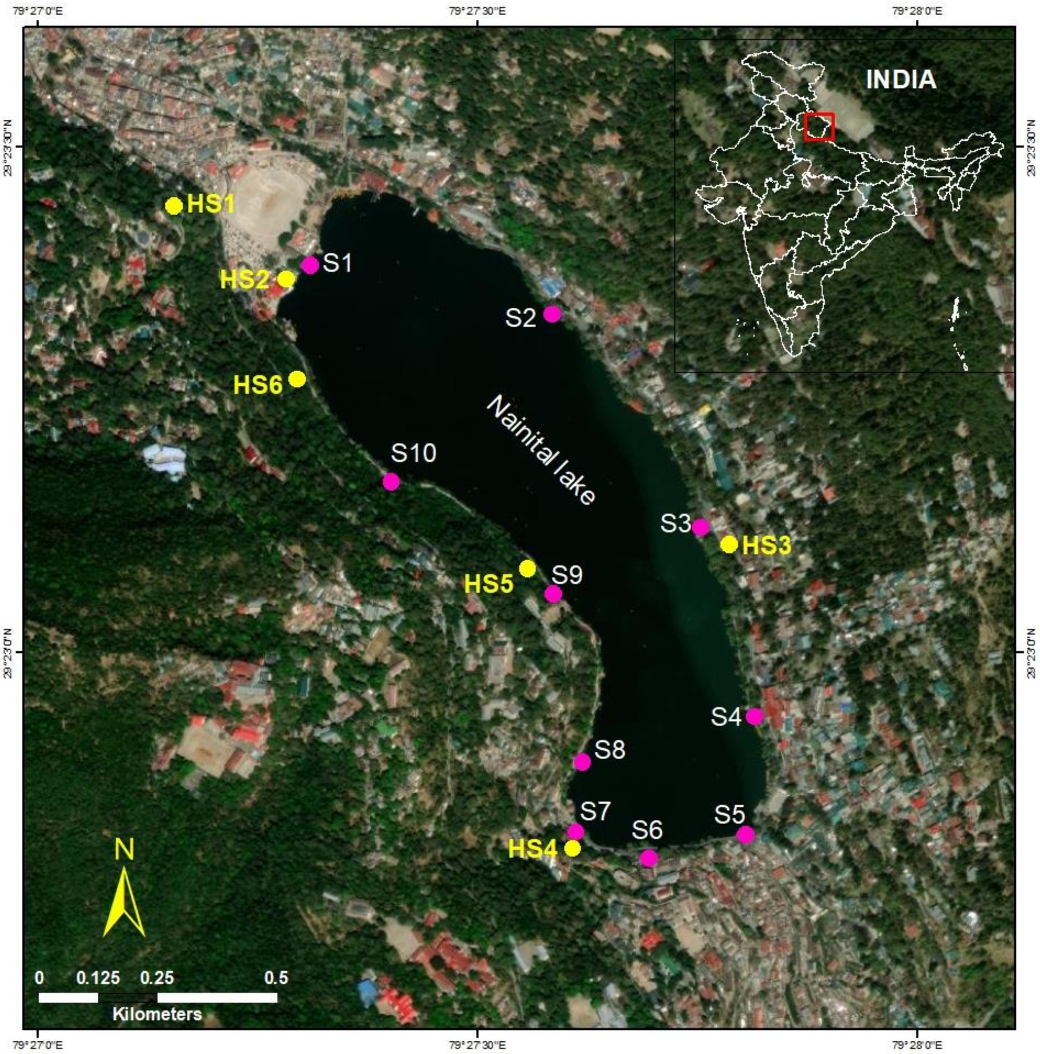


Fig. 3.5 Sampling location of the high-altitude mountain Nainital Lake in Uttarakhand, India (**Pink color circle**: S-representing the Lake sampling station, **yellow color circle**: HS-representing the Hotspot sampling station).

3.3 Analysis of microplastics in surface water and surface sediment

3.3.1 Collection of surface water

Water samples were collected from 13 different sites, i.e., surface water of the freshwater lake was collected from 10 sites (S1-S10), 1 drainage sample (HS1), 1 tubewell water sample (HS2), and 1 tap water sample (HS5) were collected. These water samples were collected using stainless steel buckets, previously rinsed with ethanol, and filtered distilled water free of microplastics. At each site, the water sample was sieved using 100 µm sieves. The filtrate was then stored in glass bottles with proper labelling and then transported to the laboratory. These filtered samples were stored in the refrigerator in the laboratory until further analysis.

3.3.2 Collection of surface sediment

Surface sediment samples from the lake were collected using the stainless-steel scoop. Duplicate samples were collected from each site. Sediment samples were collected from 7 different sites, which are HS1, S3, S6-S10. At other sites, surface sediments were inaccessible. All the samples were stored in pre-rinsed stainless-steel containers of approximately 15 L, with proper labelling, and were transported to the laboratory.

3.3.3 Analysis of microplastics in surface water and surface sediment

In the laboratory, the water samples collected were then filtered with a stainless steel of size 20 µm (**Fig. 3.6**). The contents of the sieve were transferred to glass beakers to digest the organic matter by the addition of 10mL of 30% of Hydrogen Peroxide (H_2O_2) at 60^0C for 72 hours. Further, for the density separation of the samples, 100 mL of saline solution, i.e., 120 g/L NaCl, was added to the samples. This was further filtered under vacuum pressure by using a polycarbonate membrane (1µm pore size). The filter membranes were then collected in a pre-rinsed (with 70% ethanol) sealed petri dish and dried in the air for 24 hours for qualitative and quantitative analysis (Robin et al., 2020).

In the laboratory, 10 g of sediment was weighed from each sample, and around 100 mL of filtered (0.45 µm Whatman glass fiber) seawater was added to each sample and stirred for 10 minutes to separate different size fractions of microplastics by density floatation. This was followed by wet-sieving, using a sieve of mesh size 20 µm to separate the sediment and plastic particles according to different size fractions. Further, the organic digestion of the biogenic matter was done by adding 10 mL of H_2O_2 (30%) to reduce the interference of organic impurities in subsequent procedures. These beakers were then covered with aluminium foil and put on a heating plate at 60^0C for 72 hours for digestion. After complete digestion, the supernatant was then transferred to a polycarbonate membrane filter (1 µm pore size) under vacuum filtration. Finally, with the help of cleaned steel forceps, the filter membranes were collected in a pre-rinsed, sealed Petri dish and were air-dried for 24 hours for further qualitative and quantitative analysis (Strady et al., 2021).

3.4 Visual characterization of microplastics using a Stereomicroscope

The air-dried samples were then examined under a stereomicroscope (SMZ 25; zoom range: 0.63x - 15.75x), fitted with a digital camera to determine the type of microplastics. The characterization of microplastics was done on the basis of their shape and was categorized into 5 types: (i) fiber/line (elongated, thin, straight particles), (ii) fragments (small angular, irregularly shaped particles), (iii) film (thin, soft, transparent particles), (iv) foam (lightweight particles with spongy texture), (v) pellets (spherical, cylindrical particles). On the basis of colors, these microplastics were further categorized into 6 types: white/colorless (hereafter referred to as white), red/pink (hereafter referred to as red), black/grey/brown (hereafter referred to as black), yellow/orange (hereafter referred to as yellow), green, blue and violet/purple (hereafter referred to as blue). Microplastic-like particles are collected for polymer identification using FTIR.

3.5 Identification of microplastic polymer using FTIR

The chemical composition of the plastic-like-particles was determined by using the Perkin Elmer Frontier^{TM} Fourier Transform Infrared Spectrometer (FTIR) with Attenuated Total Reflectance (ATR) (Fig. 4.6). Each sample was scanned 16 times at a resolution of 4 cm^{-1} and at a resolution range of 4000 to 450 cm^{-1}. Before placing each of the samples on the ATR-diamond crystal, it was wiped with isopropanol, and the background scan was updated. For the confirmation of the chemical composition of the polymers present in the samples, the reference spectra from the synthetic polymer ATR library ($r \geq 0.70$) were used. Special care was taken during the handling and processing of samples in the laboratory to avoid airborne contamination.

3.6 Quality assurance measures

Strict quality control measures were taken according to QC and QA criteria (Karthik et al., 2018; Robin et al., 2020). Before sampling and processing, all the field equipment (sieves, steel bucket) and glassware (e.g., glass bottles, beakers, bowls, and Petri dishes) were thoroughly rinsed twice with Milli-Q water. While handling and processing samples, extreme care was taken to avoid contamination by airborne plastics in the laboratory. Furthermore, a cotton lab coat and nitrile butadiene gloves were worn during the experiment. For the disinfection of the workplace, 70% ethanol was used. While the samples were processed in a biosafety cabinet, UV radiation was used for surface sterilization. The samples were covered with aluminium foil during the process to avoid contamination from the external environment. Before analysis, the microscope workplace was sterilized to avoid cross-contamination. Laboratory blanks were performed at different stages to ensure that there was no contamination in the samples. Meanwhile, at least twice each sample was counted to ensure accuracy and confirm highly accurate results.

3.7 Statistical analysis

For data analysis, Bubble Plotting was performed to check the abundance of MPs in the surface water and surface sediments at different sites using ArcGIS. Principal Component Analysis was performed using the software Origin Pro to analyze the relationship between the different sampling sites and colors of MPs, for surface water samples and surface sediment samples. Hierarchical Cluster Analysis was performed using the software Origin Pro to find the correlation between the different sampling sites from where the surface water and surface sediment samples were collected.

Fig. 3.6 Pictures representing the steps followed during the procedure: (a) Sample collection; (b) Sample weighing; (c) Sample drying; (d) Sieving; (e) Density-separation; (f) Organic digestion; (g) Filtration; (h) Microplastics analysis (quantitative); and (i) Qualitative analysis using FTIR

Chapter 4

RESULTS & DISCUSSION

4.1 Microplastics in the surface water of Nainital Lake

4.1.1 Spatial Distribution of MPs

The MPs were observed in all the samples of surface water collected from the Nainital Lake and its catchment area, with average concentrations ranging from 8.6 to 56.0 MPs/L in the Nainital Lake and 2.4 to 88.0 MPs/L in the hotspot's areas (HS1, HS2, and HS5) (**Fig. 4.1**). The present result indicates that there is a significant source of MPs pollution in and around Nainital Lake. The abundance of MPs in the water shows the significant distribution in and around the lake. Particularly, site HS1 was considered the hotspot that contained a significantly higher concentration of MPs, i.e., 88.0 MPs/L. HS1 is the main drain, named Bara Nala, connecting small drainage from the hilltop to the Nainital Lake. The drain (HS1) receives water from the residential areas, market areas, hotels, and spring water from the western end and can be considered the major source of MPs entering the lake. The high abundance of the MPs inside the lake is observed at sites S8 and S6 as 56.0 MPs/L and 48.0 MPs/L, which are present at the western and south-western ends of the lake, and the lowest concentration inside the lake was found at site S3 (8.6 MPs/L). The observed higher concentration of MPs is assumed to be due to the deposition of a higher number of debris, which can concentrate on this site from all the other sides of the lake. Moreover, the western and south-western end of the lake has less tourist activity and human intervention, and thus due to the less disturbance and the flow of water, the waste produced at other sides accumulates at these sites. The presence and distribution of MPs can be due to the dumping of waste along the lake shore, weathering of the plastic material, and meteorological and hydrological action (Ballent et al. 2012; Kukulka et al. 2012). Current velocity can cause the transporting of plastics from water, strong currents have a higher eroding capacity for high-density debris, transporting it to down-current areas or areas of lower density (Ballent et al., 2012). Wind action (Liu et al. 2019), floods, and landslides are also considered to add microplastics to the water body. Hence, this could have also contributed to the MPs to the lake water. The other reason could be the small surface area of the lake (11.89 km^2) and a greater number of inlets in the lake in comparison with the outlets, which can lead to accumulation, as found in Lake Naivasha, Kenya (Francis et al., 2019), and Lake Geneva, Switzerland (Faure et al. 2015), as compared with the other larger lakes. The higher number of tourists can also be considered the reason for the high concentration of microplastics in the lake. The lowest concentration at the hotspot was observed at site HS2 as 2.4 MPs/L, which is the tubewell water present at the bank of Nainital Lake. The low concentration of MPs at this site can be due to the natural filtration of water. In comparison to the other lakes studied worldwide, the results in the present study are found to contain a higher number of MPs in surface water (**Table 3**).

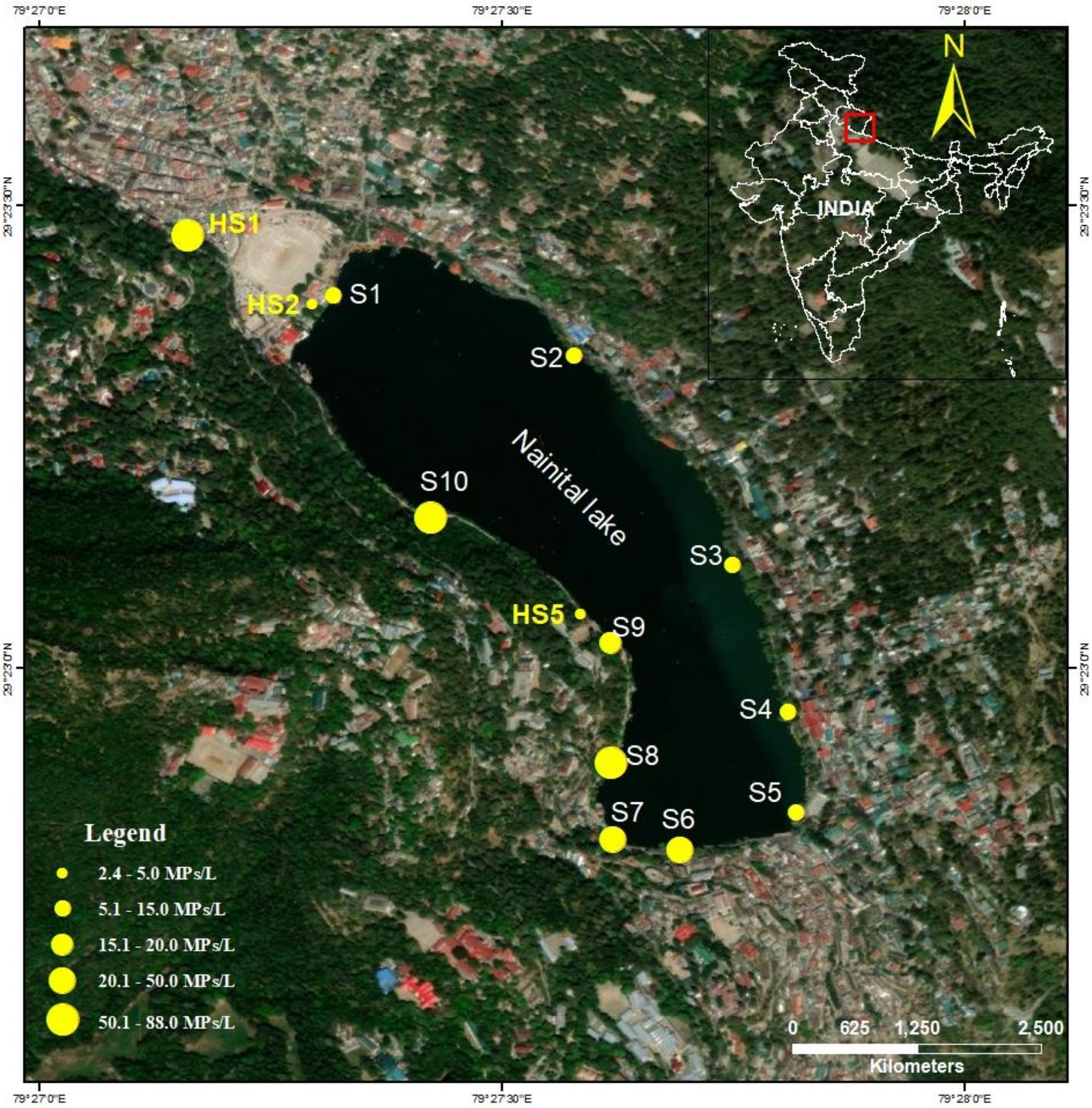


Fig. 4.1 Spatial distribution of microplastics in surface water of Nainital Lake

Table 3: Comparison of the MPs found in the present study with freshwater lakes worldwide

Fresh-water Lakes	**Location**	**Sample type**	**Surface Area**	**Altitude**	**Abundance of MPs**	**Reference**
Taihu Lake	China	Surface water and sediments	2000 km^2	3.3m	Surface water:3.4-25.8 items/L Sediment:11.0-234.6 items/kg dw	Su et al. (2016)
Dongting Lake	China	Surface water and sediment	2625 km^2	33m	West Dongting Lake:616.67 to 2216.67 items/m^3 South Dongting Lake:716.67 to 2316.67 items/m^3	Jiang et al. (2018)
Vesijärvi lake	Finland	Sediment	107.57 km^2	87m	Sediment:395.5 ±90.7 MPs/kg	Scopetani et al. (2019)
Lake Naivasha	Kenya	Surface water	139 km^2	1884 m	Surface water:0.407± 0.135 particles/m^2	Francis et al. (2019)
Lake Kallavesi	Finland	Surface water	478.1 km^2	82m	Manta trawled sample:0.27 ±0.18 MPs/m^3 Pump filtered samples:1.8±2.3, 12±17 and 155 ± 73 MPs/m^3	Uurasjärvi et al. (2019)
Poyang Lake	China	Surface water and sediment	1000-3000 km^2	16.5m	Surface water:5–34 items/L Sediment:54–506 items/kg	Yuan et al. (2019)
Lake Victoria	Africa	Shore and Lake Sediment	68,800 km^2	1135m	Shore sediment:0-1102 particles/kg Lake sediment:0-108 particles/kg	Egessa et al. (2019)
Lake Guaíba	Porto Alegre, Brazil	Surface water	496 km^2	3m	Surface water:11.9±0.6 to 61.2±6.1 items m^{-3}	Bertoldi et al. (2020)
Lake Sassolo	Switzerland	Water and sediment	0.05 km^2	2074 m	Water:2.6 MPs/L Sediment:33 MPs/kg	Velasco et al. (2020)

Fresh-water Lakes	Location	Sample type	Surface Area	Altitude	Abundance of MPs	Reference
Dimon Lake	Carnic Alps, Italy	Water	0.6ha	1872 m	Water:0.33 items L^{-1}	Pastorino et al. (2020)
Lake Ziway	Ethiopia, Africa	Shoreline sediment	442 km^2	1636m	Shore sediment:0.05 - 36233) mg/kg_dw	Merga et al. (2020)
Phewa Lake	Nepal	Surface water	5.72 km^2	763-2482 m	Winter season:2.96±1.83 particles/L Rainy season=:.51 ±0.62 particles/L	Rajeshwori et al. (2021)
Renuka Lake	Himachal Pradesh, India	Water and sediment	254ha	620 m	Water:02–64 particles/L Sediment:15–632 particles/kg dw	Ajay et al. (2021)
Nainital Lake	India	Surface water and surface sediment	11.89 Km^2	1,934m	Surface water:2.4-88.0 MPs/L Surface sediment:4.0±0.0 to 10.6±15.6 MPs/g	**Present Study**

4.1.2 Physical Features and potential sources of MPs

The sizes, shapes, and colors of the MPs were observed to be diverse. In the surface water samples analyzed, **t**he fibers were observed as the most abundant item, followed by fragments, films, and pellets. The fiber makes up 94% of the surface water sample, followed by the fragment (4%) and film (2%) (**Fig. 4.2**), which can originate from larger plastic items (Singh and Sharma, 2008). It can be concluded that the secondary MPs are the most dominant types of MPs in the surface water of the Nainital Lake, which shows the improper waste management strategies in the area. Fibers can be released from textile production, washing, and their natural aging (Yang et al., 2021b), boating gears, ropes, and decoration material in temples. Fibers can be carried away by winds and thus can enter freshwater sources by air movements and rainfall (Kaliszewicz et al., 2020). The results show similarity with Lake Hovsgol, Mongolia (Free et al., 2014), and Lake Naivasha, Kenya (Francis et al., 2019), in which the fibers, fragments, and films were observed in the surface waters. Fragments and films can be produced from the degradation of larger plastic materials such as plastic bags, paint from boats, and fragments from fiber-reinforced plastic such as bottles and packaging materials.

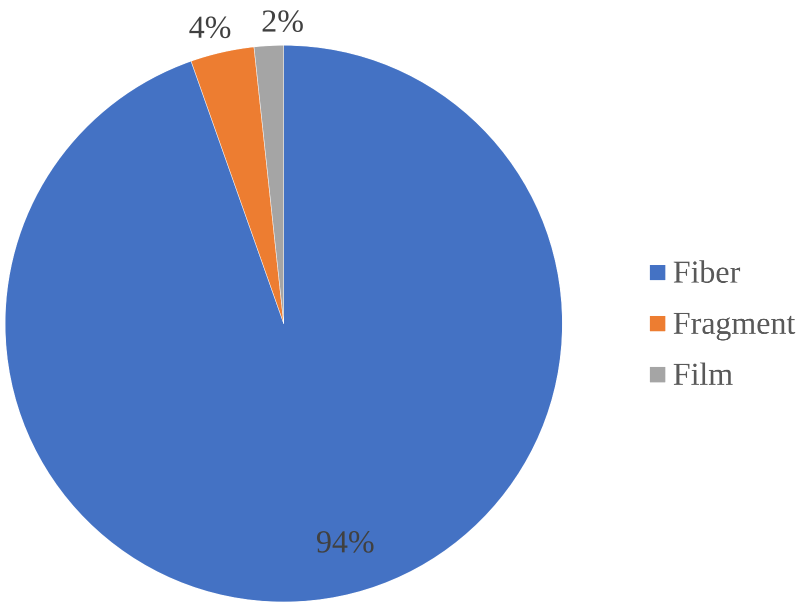


Fig. 4.2 Shape variation of the microplastics in the surface water of Nainital Lake

MPs of size 0-1 mm were found to be the most abundant in the surface water samples, and the least was found to be >5mm. The dominant size range was observed as 0-1 mm (51%), followed by 1-2 mm (31%), 2-5 mm (17%), and >5 mm (1%) (**Fig. 4.3**). The results are similar in comparison with Taihu Lake, China (Su et al., 2016), Phewa Lake, Nepal (Rajeshwori et al., 2021), and Great Laurentian Lakes, USA (Driedger et al., 2015), where the small-sized microplastics were found to be dominant. According to Ding et al. (2019) and Zbyszewski et al. (2014), higher MPs in smaller size ranges indicate that the plastic material was retained in the water body for a long time, which may have caused fragmentation due to weathering, chemical, and physical processes. The small-sized MPs are considered to be a greater risk, as they can resemble the plankton (Sivan, 2011; Wright et al., 2013), have higher surface area per unit mass/volume, and can act as vectors (Retama et al., 2016), adsorb toxic chemicals or additives (Mason et al., 2016), which can be ingested by the aquatic organisms.

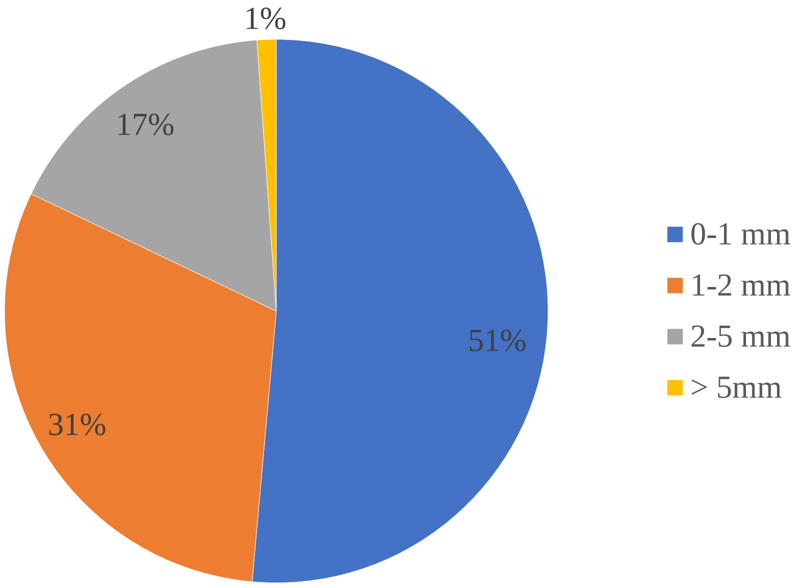


Fig. 4.3 Sizes of microplastics observed in surface water of Nainital Lake

The colored MPs were found to be abundant in the water samples analyzed. Blue (51%) was found to be the most prevalent color in the water samples, followed by red (21%), black (20%), green (4%), yellow (3%), and white (1%) (**Fig. 4.4**). The results are similar in comparison to the MPs found in Koshi River by Yang et al. (2021a) and Poyang Lake, China (Yuan et al., 2019), in which colored MPs were found to be dominant. The greater percentage of colored MPs in the samples provides strong evidence for anthropogenic influx as a source of synthetic materials, but it additionally indicates the diversity of their origins (Stolte et al., 2015), such as plastic toys, packaging material, and textiles. The white MPs can be produced by packaging bottles, plastic bags, or environmental weathering/bleaching as a result of persistence in the environment for a prolonged period of time (Tsering et al., 2022). The MP's color and size are also linked to the ingestion of MPs by aquatic organisms if it resembles their prey (Wright et al., 2013).

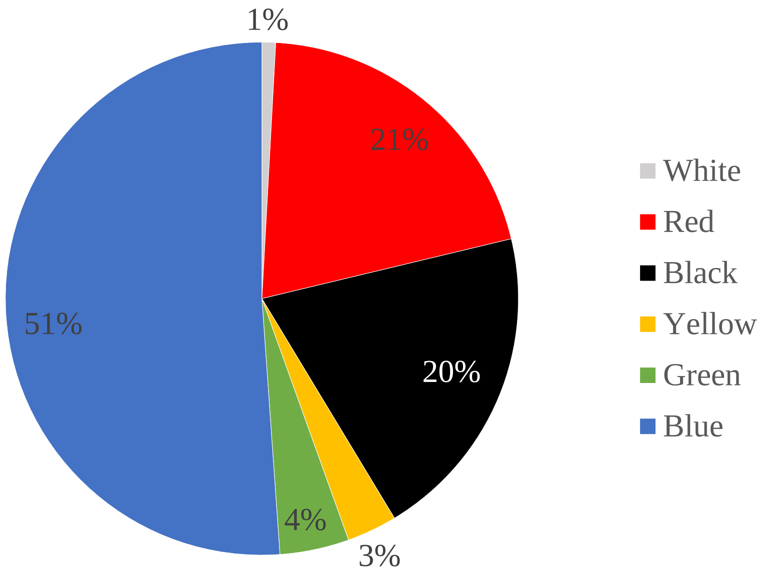


Fig. 4.4 Colour variation in microplastics in surface water of Nainital Lake

4.1.3 Chemical Composition of MPs

About 50% of MPs (representative samples) from the surface water samples were analyzed for the identification of the MPs polymers through FTIR analysis. The identified microplastics were classified as PP, HDPE, PE, PET, Polybutyl acrylate, and LDPE (Cellophane). HDPE (30%) and PE (30%) were the most prevalent polymers, followed by PP (17%), PET (15%), LDPE (5%), and Polybutyl acrylate (3%), as shown in **Fig. 4.5, 4.6** and **4.7**. The similar results were observed in Lake Sassolo, Switzerland (Velasco et al., 2020); Lake Guaíba, Brazil (Bertoldi et al., 2020); Lake Naivasha, Kenya (Francis et al., 2019), where PE was found to be the most abundant MPs. Whereas the results deviate from others as HDPE is also found to be dominant in this study. HDPE is used in various applications, such as in plastic bottles, plastic pipes, and textiles. PE and PP are the most abundant plastic used worldwide for various purposes, such as raw materials for textiles, food packaging, shopping bags, bottles, straws, toys, and housewares. PET can be used in textiles for the production of clothes and blankets, food and liquid containers, bags, and housing material (Francis et al., 2019). Thus, PE, HDPE, PP, and PET can be considered the major sources of fibers and fragments in the lake.

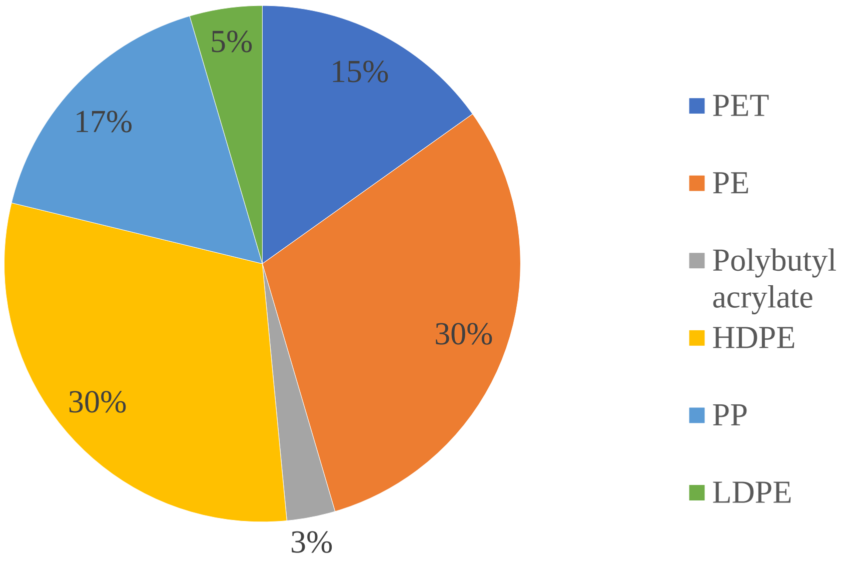


Fig. 4.5 Polymer composition of MPs present in surface water of Nainital Lake

The fibers released by washing can be the major sources of MPs (Hernandez et al., 2017) and can be released into the lake by sewage discharge, surface run-off, and atmospheric deposition (Francis et al., 2019). LDPE is used in packaging material and can be considered a major component contributing to the formation of films in lake water. Polybuty acryl can act as a raw material for fiber processing agents, rubber, adhesives, and paints. The density of PE, HDPE, PP, LDPE, and Polybutyl acryl is less than that of freshwater; thus, they can float on the surface of the water. However, in this study, PET has also been observed which has a higher density than water, similar to Lake Naivasha, Kenya, which can be due to various factors such as the large surface-to-volume ratio of MPs, biofouling, and mechanical forces like waves and tides that may influence the position of the particles in the water column (Zhao et al. 2015) and can affect the vertical distribution of MPs in aquatic environments (Francis et al., 2019).

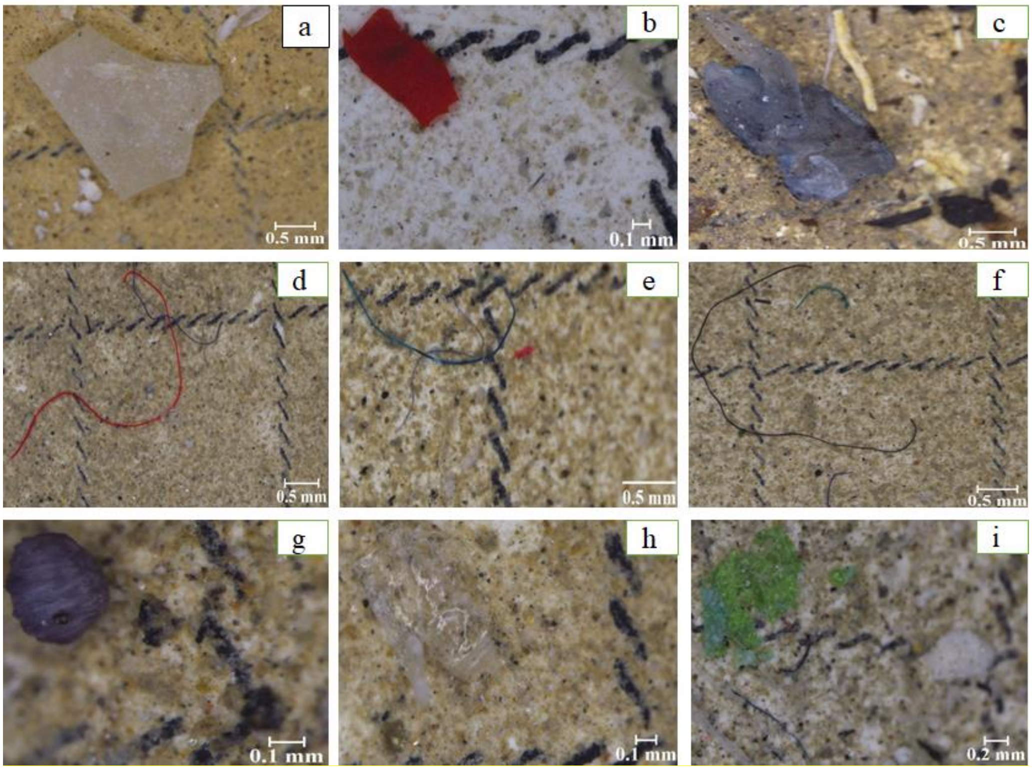
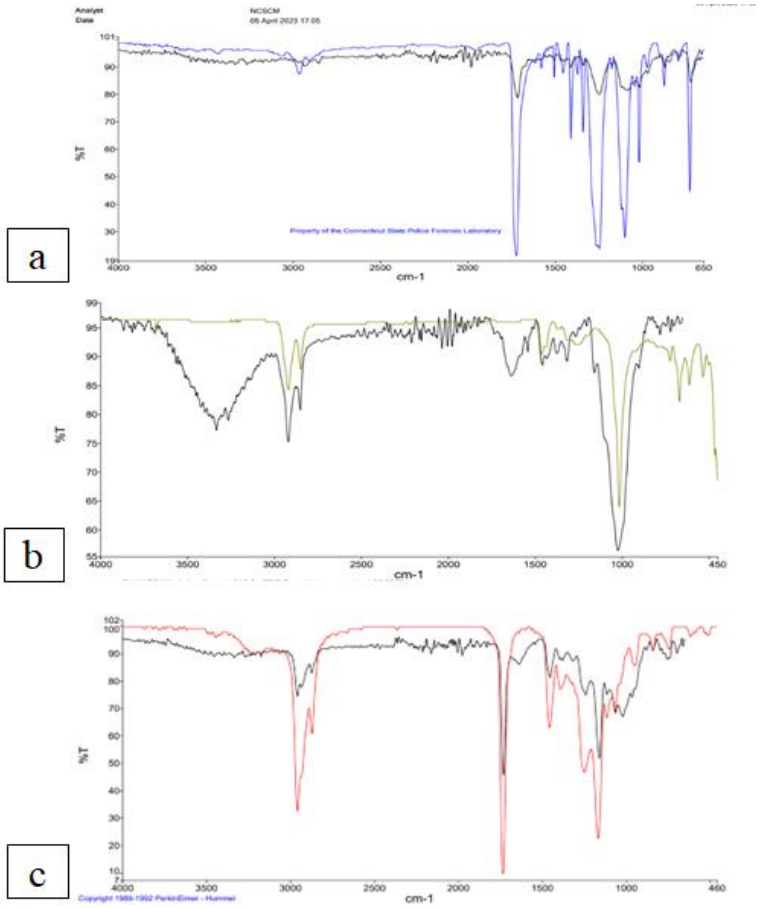


Fig. 4.6 MPs observed in the surface water and sediments representing different colors and shapes: (a)- (c) Fragments; (d)-(f) Fibers; (g) Pellet; (h)-(i) Film



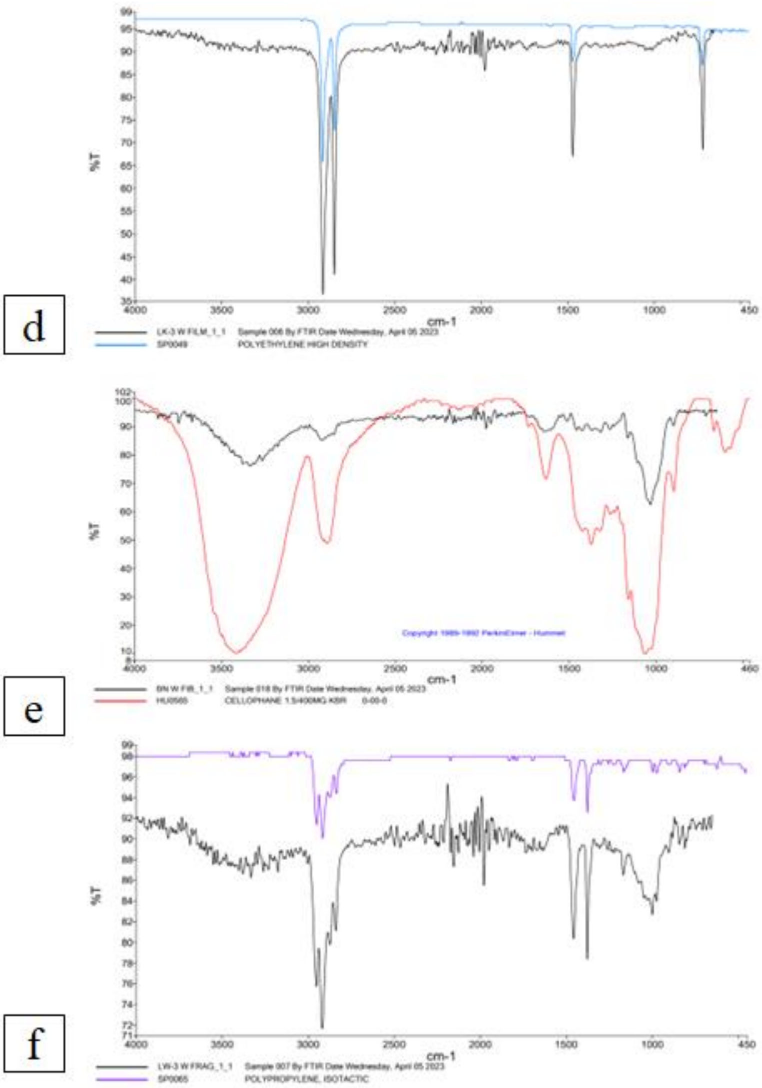


Fig. 4.7 FTIR spectrums of MPs in the surface water of Nainital Lake: (a) PET; (b) PE; (c) Polybutyl acrylate; (d) HDPE; (e) LDPE; (f) PP; the Black line represents the standard

4.1.4 Principal Component Analysis

The Principal Component Analysis (**Fig. 4.8**) showed that the sites S8 and S9 show a positive correlation with the colors such as white, red, and orange. The sites S6 and S7 show a positive correlation with colors such as green, blue, and black. Whereas the sites S1, S2, S3, S4, and S5, were not correlated with any colors.

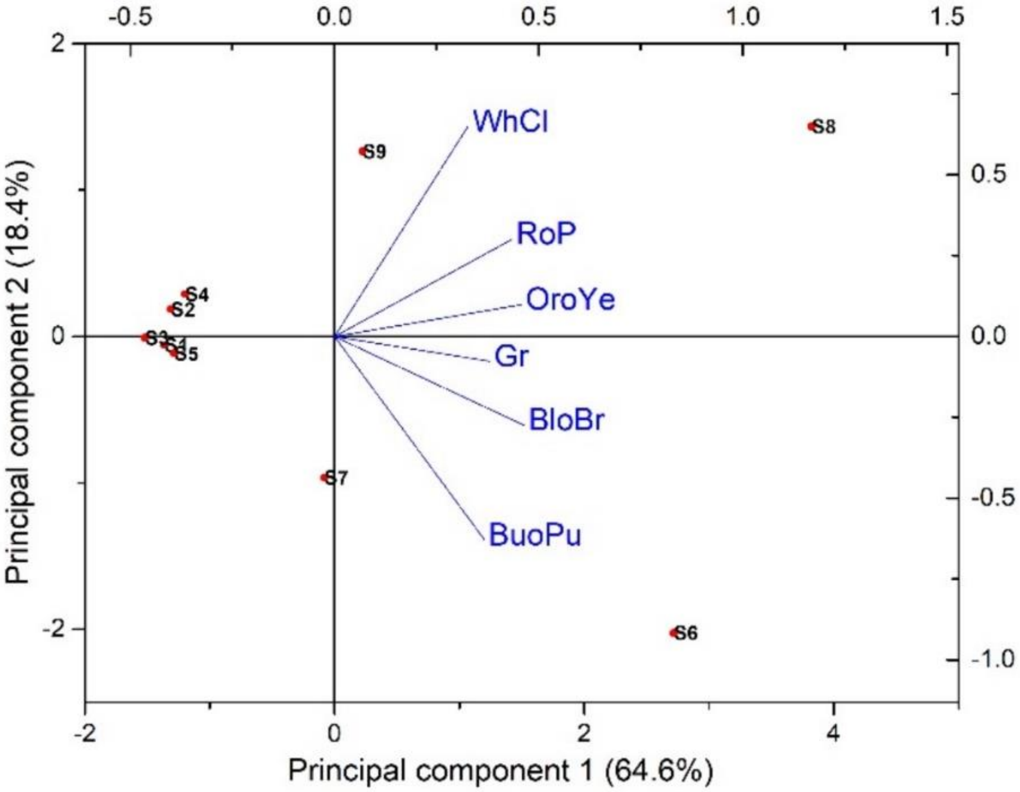


Fig. 4.8 Principal Component analysis for MPs colors present in the surface water of Nainital Lake

4.2 Microplastics in the surface sediments of Nainital Lake

4.2.1 Spatial Distribution of MPs

The MPs were discovered in the surface sediment collected from the Nainital Lake and its catchment area, with average concentrations in the Nainital Lake ranging from 0.4±0.0 to 10.6±1.56 MPs/g, and at hotspot site HS1 as 0.6±0.49 MPs/g, respectively (**Fig. 4.9**). The MPs were found in all the surface sediment samples like in the high-altitude lake Sassolo, Switzerland (Velasco et al., 2020) and in the Pangong Lake, Tsomoriri Lake, and Tsokar Lake, of Indian Himalayas (Tsering et al., 2022). The abundance of MPs in the sediment samples shows the uneven distribution in and around the lake. The highest concentration of MPs in the surface sediment samples of Nainital Lake was observed at site S3, which contains 10.6 MPs/g, which may be due to anthropogenic activities such as boating, infrastructure development, residential areas, and hotels in the vicinity of the lake area (Ajay et al., 2021). The direct disposal of plastic waste by tourists (Ajay et al., 2021) and the direct disposal of sewage through the drains into the lake can also lead to the concentration of MPs at the corners of the lake. The sites S6, S7, S8, and S10 at the western and south-western side of the lake also contains a higher number of MPs. This can be due to the lesser disturbance and higher accumulation of debris, which can concentrate on this side from all the other sides of the lake. Also, the lower water current on this side and direct disposal of plastic waste can also contribute to the higher number of MPs.

Current velocity can cause the removal of plastics from water, strong currents have a higher eroding capacity for high-density debris, transporting it to down-current areas or areas of lower density (Ballent et al., 2012). Wind action (Liu et al. 2019), floods, and landslides are also considered to add microplastics to the water body. The lowest concentration of MPs was found at the hotspot site HS1, which is a main drainage named Bara Nala, connecting small drains from the hilltop to the Nainital Lake. The higher altitude and continuous flow of water in the drain can be assumed as one the reasons for the deviation of MPs count in sediment than from the MPs found in the water from the same site. In comparison with other lakes studied worldwide, the surface sediment in the present study contains a higher concentration of MPs (**Table 3**).

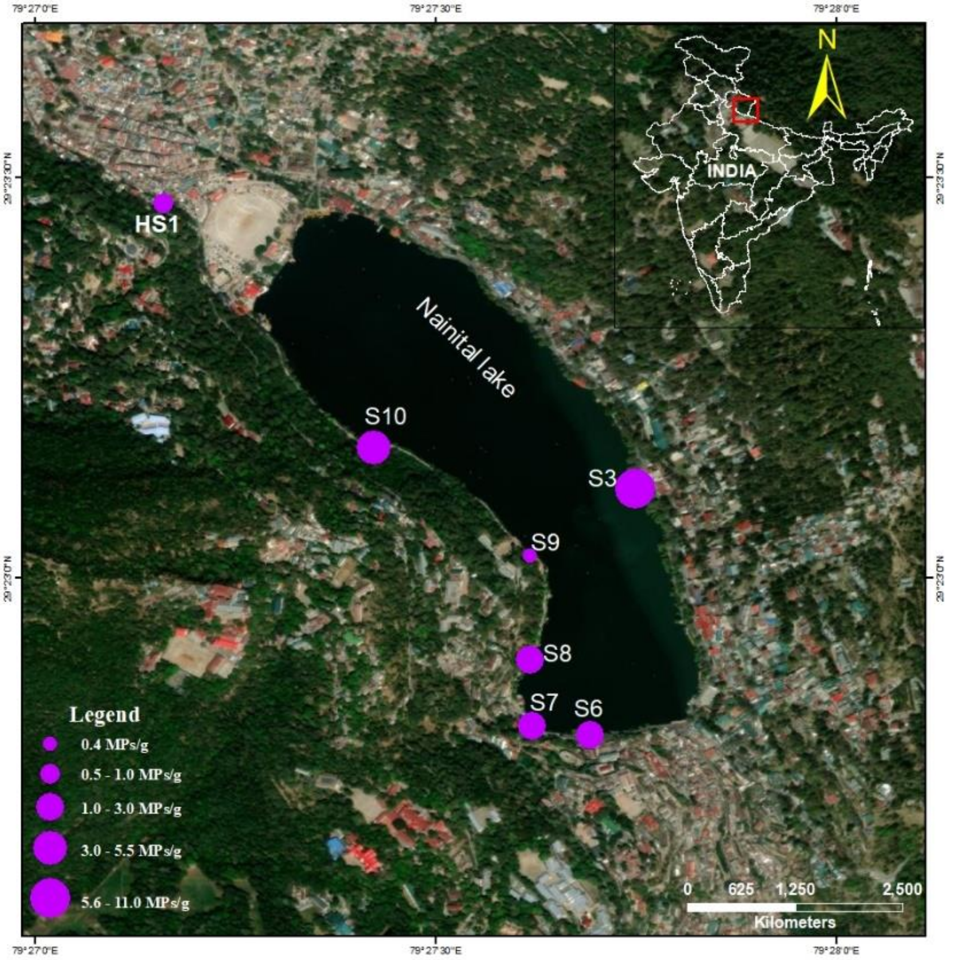


Fig. 4.9 Spatial distribution of microplastics in surface sediment of Nainital Lake

4.2.2 Physical features and potential sources of MPs

The sizes, shapes, and colors of the MPs were diverse in the surface sediments analyzed. Fiber was observed as the most abundant item in the surface sediments, followed by fragments, films, and pellets. The fiber makes up 89% of the total, followed by fragments (11%), while pellets and films comprised <1% (**Fig. 4.10**). These can be released from the degradation of the larger plastic items (Singh and Sharma, 2008), and thus it can be considered that the secondary sources of MPs are abundant in the vicinity of the lake. The results are similar to the Lake Sassolo, Switzerland (Velasco et al., 2020), Poyang Lake, China (Yuan et al., 2019), and Lake Victoria, Africa (Egessa et al., 2019), where fibers were found to be the predominant microplastics in the sediments. Fibers can be released by textile production, washing, and their natural aging (Yang et al., 2021b), boating gears, ropes, and decoration material in temples. Fibers can be carried away by winds and thus can enter freshwater sources by air movements and rainfall (Kaliszewicz et al., 2020). Fragments and films can be produced from the degradation of larger plastic materials such as plastic bags, paint from boats, bottles, and packaging materials.

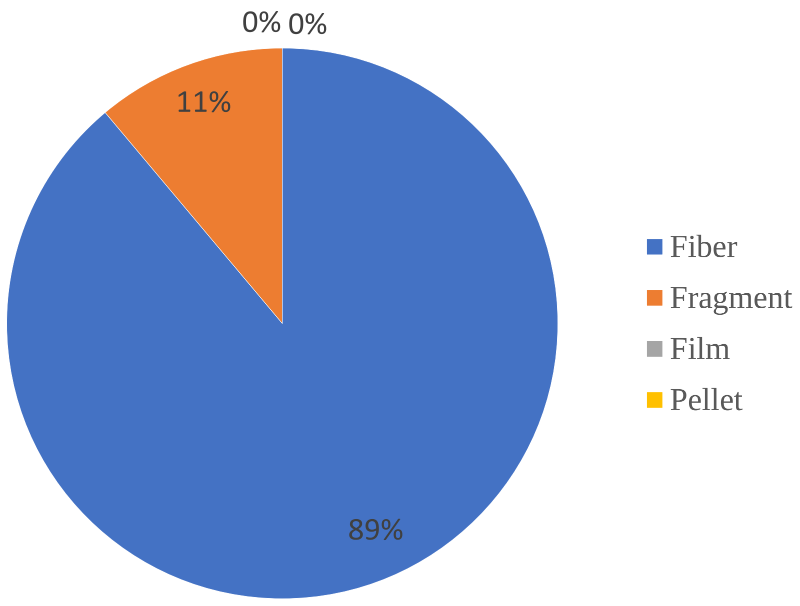


Fig. 4.10 Shape variation of the microplastics in the surface sediment samples

The size 0-1 mm was found to be the most prevalent in the surface sediment samples, and the least was found to be >5 mm. The maximum abundance was found in the size range of 0-1 mm (67%), followed by 2-5 mm (33%), 1-2 mm, and >5 mm (0-1%) (**Fig. 4.11**). The dominance of small-sized MPs has also been observed in Taihu Lake, China (Su et al., 2016), Lake Hovsgol in Mongolia (Free et al., 2014), and Lake Victoria, Africa (Egessa et al., 2019). According to Zbyszewski et al. (2014), mechanical forces and photochemical processes are the key factors that cause larger debris of plastic to break up into smaller MPs. At present, microfibers are believed to be the most prevalent type of MPs in the environment, and like fragments, they are easily dispersed globally and can reach remote places after dry or wet deposition events (Ryan et al., 2020). The high persistence of microfibre MPs in the water column and the likelihood that they may be ingested by aquatic organisms make them an environmental concern (Welden and Cowie, 2016).

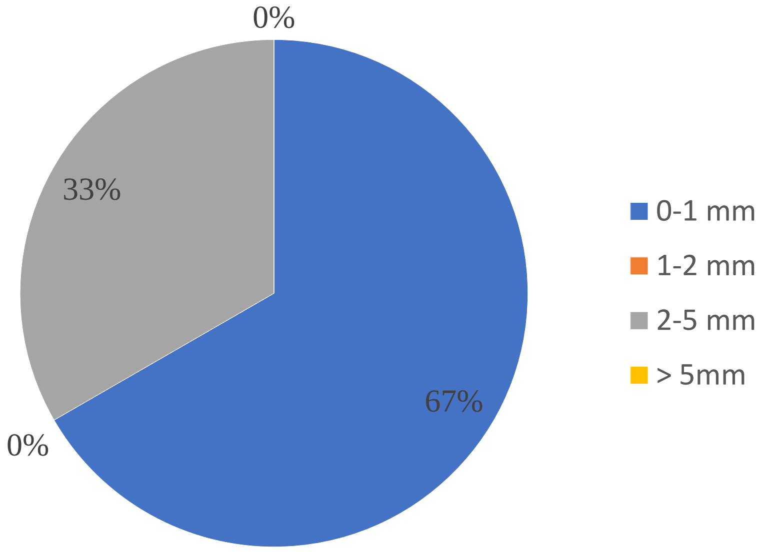


Fig. 4.11 Sizes of microplastics observed in surface sediment of Nainital Lake

In the surface sediment samples analyzed, the colored items were found to be abundant. Red (34%) was the most prevalent color, followed by black (33%), blue/purple (22%), green (11%), yellow and white (0-1%) (**Fig. 4.12**). According to Stolte et al. (2015), color is not a permanent factor and can be bleached due to environmental processes. The colored particles are observed to be dominant in the sediment, similar to the findings in the sediments of Poyang Lake, China (Yuan et al., 2019) and Lake Naivasha, Kenya (Francis et al., 2019). The greater percentage of colored MPs in the samples provides strong evidence for anthropogenic influx as a source of synthetic materials, but it additionally indicates the diversity of their origins (Stolte et al., 2015) such as the plastic toys, packaging material, textiles, and, vehicles. The white or colorless MPs can be produced by packaging bottles, plastic bags, or environmental weathering/bleaching as a result of persistence in the environment for a prolonged period of time (Tsering et al., 2022). The MP's color and size are also linked to the ingestion of MPs by aquatic organisms as it resembles their prey (Wright et al., 2013).

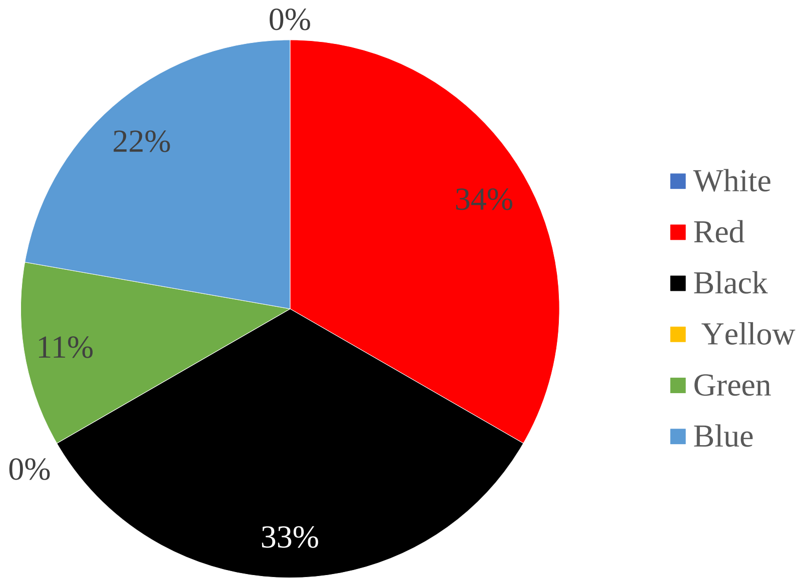


Fig. 4.12 Color variation in microplastics in surface sediment of Nainital Lake

4.2.3 Chemical Composition of MPs

About 50% of MPs (representative samples) from the surface sediment were analyzed for the identification of the MPs polymers through FTIR analysis. The microplastics were identified as PP, PE, and LDPE (Cellophane). PE was the most prevalent (50%) polymer, followed by PP (43%), and the least was found to be LDPE (7%), as shown in **Fig. 4.13.**

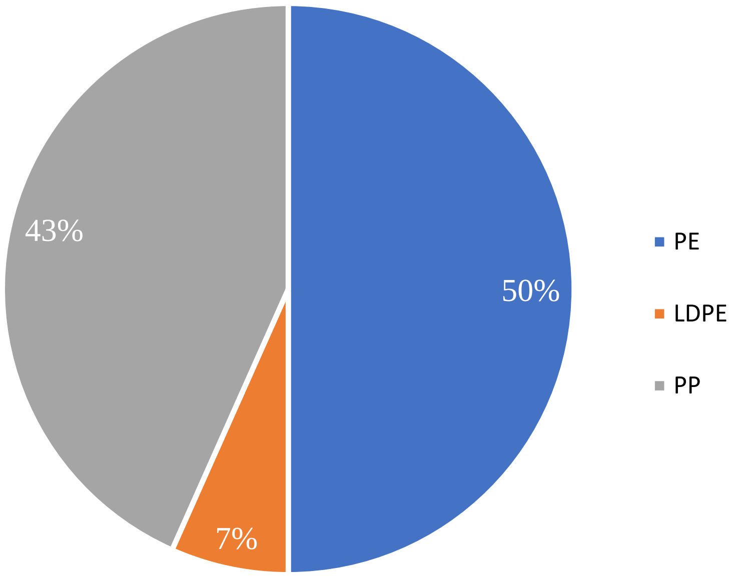


Fig. 4.13 Polymer composition of MPs present in surface sediment of Nainital Lake

Lake Naivasha, Kenya (Francis et al., 2019), Lake Sassolo, Switzerland (Velasco et al., 2020) and Lake Ziway, Africa (Merga et al., 2020), showed similar results where PE and PP were found to be the dominant polymers in the sediments. PE and PP are the most abundant plastic used worldwide for various purposes, such as raw materials for textiles, food packaging, shopping bags, bottles, straws, toys, and housewares. Thus, PE and PP can be considered the major sources of fibers and fragments in the lake sediments. LDPE is used in packaging material and can be considered a major component contributing to the formation of films in lake water. LDPE has been observed in sediments of Lake Garda, Italy (Imhof et al., 2013) and Vembanad Lake, India (Sruthy and Ramasamy, 2016). Due to the lower density of PE, PP, and LDPE, less than that of freshwater, they can float on the surface of the water. The FTIR spectrum of the following MPs is shown in **Fig. 4.14**

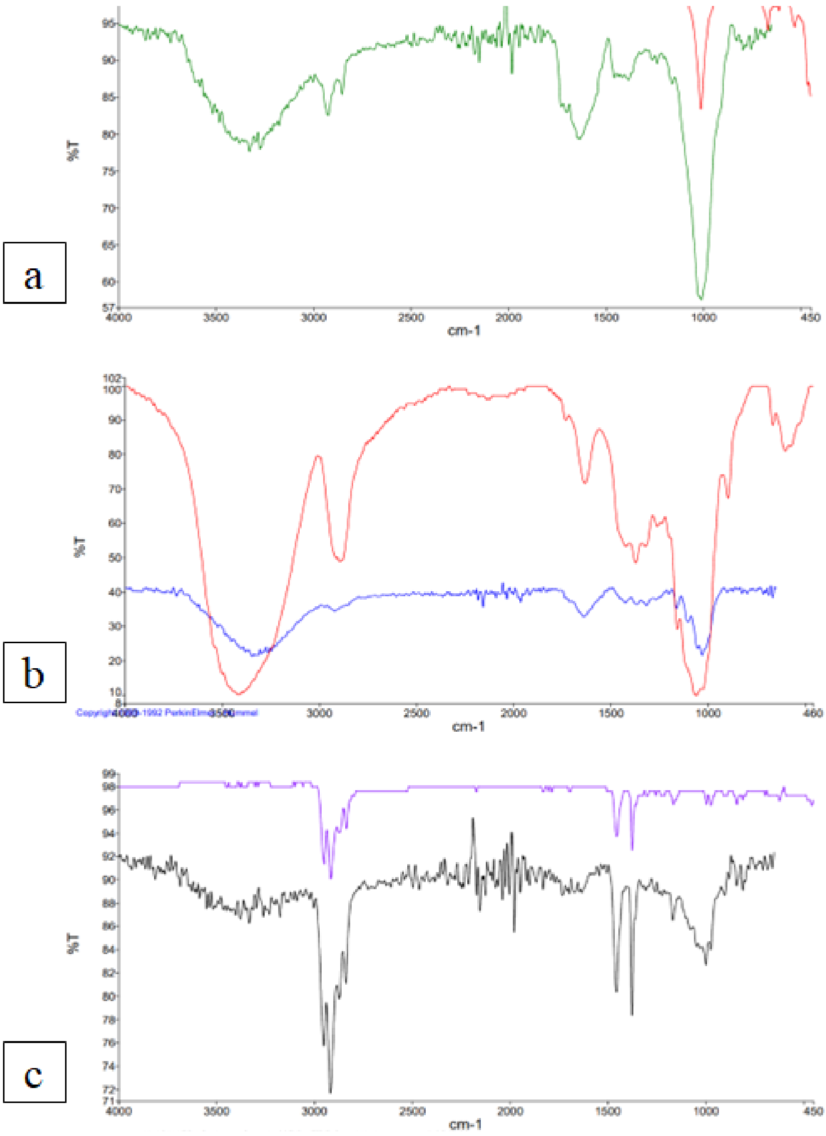


Fig. 4.14 FTIR spectrums of MPs in the surface sediment of Nainital Lake: (a) PE; (b) LDPE; (c) PP.

4.2.4 Principal Component Analysis

The Principal Component Analysis (**Fig. 4.15**) showed that site S3 shows a positive correlation with the colors such as White and Orange. The higher influence of the tourists at this site can be considered as the reason for more accumulation of white (or colorless) MPs. The direct disposal of plastic water bottles, polybags, and other packaging items into the lake and other drains meeting the lake leads to the release of white or colorless MPs, which can get accumulated into the surface sediments, whereas yellow (or orange) color can be due to the disposal of colored plastic material used by tourists. The site S10 shows a positive correlation with colors such as Red, Green, Blue, and Black. The disposal of household items, laundry, and synthetic materials at this site can cause the accumulation of colored MPs. Whereas the sites S6, S7, S8, S9, and HS1 were not correlated with any of these colors, which can be due to the less abundance of MPs as compared to sites S3 and S10.

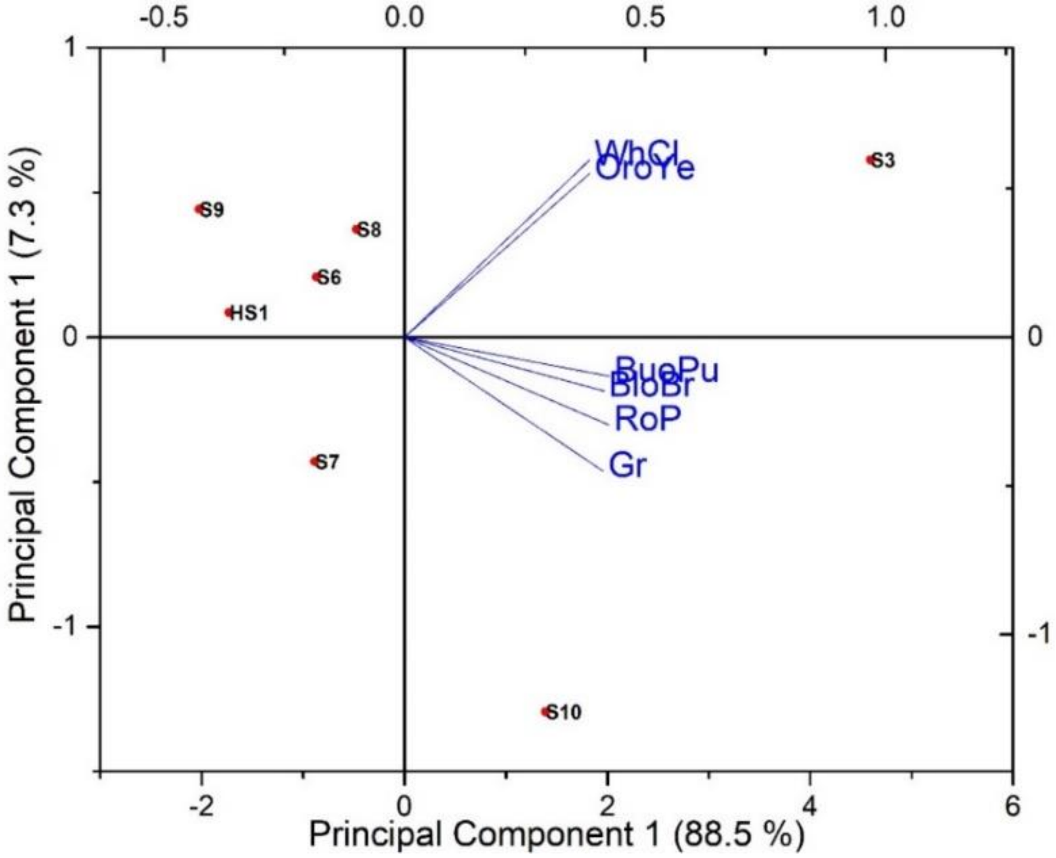


Fig. 4.15 Principal Component Analysis for MPs colors present in the surface sediments of Nainital Lake

4.3 Hierarchical Cluster Analysis

The hierarchical cluster analysis was performed based on the abundance of MPs in surface water and surface sediments. **Fig. 4.16** shows the dendrogram of the surface water and surface sediment sampling sites. From the dendrogram, it is visible that there are two main clusters. Cluster 1 is further divided into 4 sub-clusters. The sites Sw1 and Se3 are closely related, sites Sw3 and Se10, and sites Sw4 and Sw5 show close similarity. These results are reasonable as these sites have a lower number of MPs due to the transferring of plastic debris from the areas of higher current to down-current areas (Ballent et al., 2012). Whereas Sw3 and Se10 show similarity, which can be due to the direct disposal of debris into the lake or may be due to the discharge of sewage into the lake via drains. Sub-cluster 1 is distantly similar to sub-cluster 2, which is reasonable as sites Se6, Se7, Se8, and Se9 are less used by the tourists and have less population, and due to the less disturbance and water current. Sites Sw7 and Sw9 are closely related due to the dumping of waste at the lake shore or the direct discharge of sewage via drains into the lake. Sites Sw6 and Sw8 are the most distantly similar sites due to anthropogenic activities, sewage discharge, and population differences in both sites.

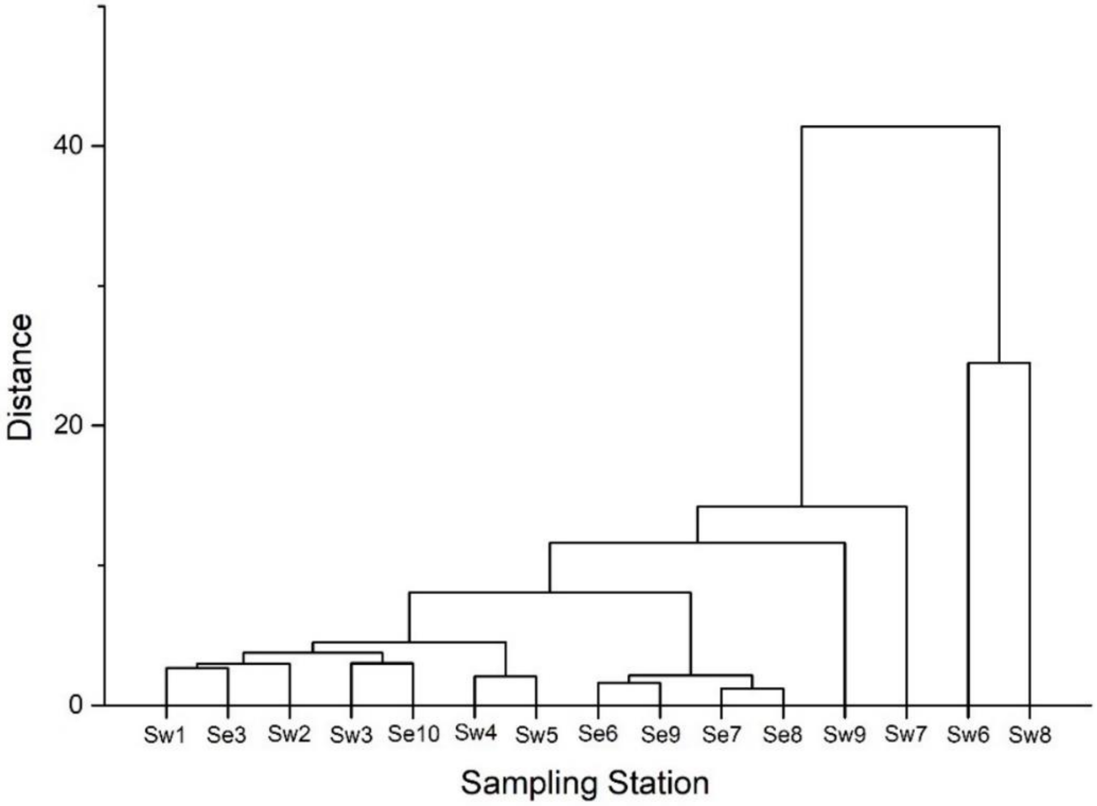


Fig. 4.16 Hierarchical Cluster Analysis showing the MPs abundance in surface water and surface sediments of Nainital Lake

4.4 Plastic Composition of Litter in the Nainital Lake

The litter was collected manually from the hotspot sites identified as HS3, HS4, and HS6 in the Nainital Lake. The polymer composition of the plastic waste was identified by the FTIR analysis. The plastic types in the waste samples were identified as PE, PP, Rayon, PS, Phenoxy resin, Poly terephthalate, and Acrylonitrile/Styrene. PP (23%) was found to be the most abundant type of plastic polymer in the litter, followed by Poly terephthalate (22%), PE (11%), Rayon (11%), Phenoxy resin (11%), and Acrylonitrile/Styrene (11%) as exhibited in **Fig. 4.17**.

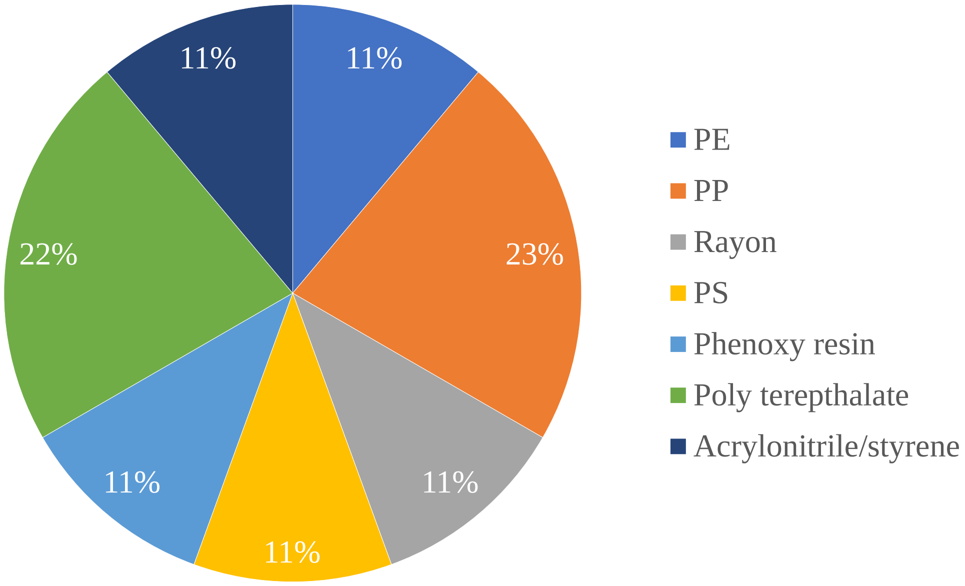


Fig. 4.17 Polymer composition of plastics present in litter collected from Nainital Lake

PE and PP are the most abundant plastic used worldwide for various purposes, such as raw materials for textiles, food packaging, shopping bags, bottles, straws, toys, and housewares. PP is used in making hard plastic items such as textile floor coverings and carpets. PS is used in the manufacturing of disposable plastic cutlery and packaging of food items, whereas acrylonitrile styrene is used in the manufacture of clothing and textiles such as sportswear, fleece jumpers, and carpets. PET can be used in textiles for the production of clothes and blankets (Francis et al., 2019), food and liquid containers, bags, and housing material. Rayon is not plastic, but being one of the common semi-synthetic materials used as raw material for the production of textiles, blankets, carpets, cigarette filters, decoration material in temples, and surgical wraps and bandages, its presence has been marked in various environments as microfibers. Rayon fabrics degrade faster in the environment, and thus they can release more fibers as compared to polyester during washing (Zambrano et al., 2019). **Fig. 4.18** represents the presence of plastic waste in the Nainital Lake, which can act as the major source of the MPs in the surface water and surface sediment.

Fig. 4.18 Litter accumulation in Nainital Lake

Phenoxy resins can be used to modify the polymers such as PE, PA, and many thermosetting plastic polymers such as PET and Nylon. Thus, PE, PP, PS, Rayon, acrylonitrile styrene, Phenoxy resins, and PET can be considered the major sources of fibers and fragments in the lake. The fibers are released by washing and can be the major sources of Microfibers (Hernandez et al., 2017) and can be released into the lake by sewage discharge, surface run-off, and atmospheric deposition (Francis et al., 2019).

Chapter 5

SUMMARY AND CONCLUSION

Microplastics were observed in the surface water and surface sediments of Nainital Lake, and the highest abundance in water was found in the major inflowing drain, Bara Nala, into the lake. The abundance of MPs in water and sediments shows almost similar spatial distribution. The western and south-western sides of the lake were found to have higher MPs concentration due to the higher accumulation of waste and discharge from the canals. The hydrodynamic conditions of the lake and water current can also lead to a higher accumulation of MPs at the down-current side of the lake. The sediment sample was also found to be higher at one point on the eastern side due to the discharge of untreated water by the canal into the lake. This shows that the lake is highly affected by the presence of untreated water present in the inflowing drains from residential areas, construction activities, and springs. The tourism is also seen to have higher impacts by the direct discharge of plastic waste into the rivers. The similar polymer found in the litter collected from the lake and the MPs in water and sediments show their common origin, i.e., the waste disposed of in lakes is also leading to the production of MPs. The polymer components for the abundance of fibers, followed by fragments and films in the surface water and sediment samples, show higher use of synthetic material and anthropogenic activities in the vicinity of the lake, such as laundering, stormwater collection, boating, and direct disposal of plastic waste and its degradation. The higher concentration of smaller size MPs (0-1 mm) shows the degradation and longer retention time of the plastic debris in the lake. The lake water is the main source of drinking water for the residents of the area. As per the results of the present study, a small concentration of MPs is found in the tubewell and drinking water, showing the risks associated, and thus it is important to monitor the sources and transport of MPs into the lake water. The abundance of small-sized MPs also depicts the need for filtration using small-size filters in treatment plants. Colored MPs were predominant in the samples showing the impacts of anthropogenic activities on the lake. The run-off catchments releasing untreated water into the lake via several drains and tourist activities can be considered as the major source of MPs into the lake and can affect the aquatic fauna and aesthetic value of the lake. The measures should be taken to reduce the sewage load into the lake, and treatment of sewage water should be done before entering the lake. The scientific measures should be taken for the filtration of lake water used for drinking. The manual cleaning of the lake from the sides, especially from the areas less frequently used by the tourists, should be done regularly in order to reduce the load of plastic debris in the lake.

Chapter 6

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