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Research Paper

Assessment of spatial distribution, sources, and ecological risks of microplastics in the estuarine and coastal regions of the northern Bay of Bengal*

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Abstract Microplastics (MPs) have recently emerged as a significant environmental problem with devastating consequences for organisms. Understanding MPs pollution in the Bay of Bengal is crucial for assessing its ecological impact on marine biodiversity and human health. This study examined the occurrence, spatial distribution, physical and chemical properties, ecological risks, and probable sources of MPs in estuarine and coastal marine environments in the northeastern Bay of Bengal. The average concentration of MPs in surface water of the Karnaphuli estuary, the Meghna estuary, and the southeastern coastal region were 916.7±462.6 items/m^3, 462.9±324.5 items/m^3, and 350.0±190.5 items/m^3, respectively, varying from 105.0±324.5 items/m^3 to 1 640.0±462.6 items/m^3. In the sediments of the Karnaphuli estuary, the Meghna estuary, and the southeast coast of Bangladesh, the average amount of MPs were 94.3±33.1 items/kg, 157.6±89.0 items/kg, and 134.3±38.7 items/kg, with a range of 60±33.1 items/kg to 334.3±89.0 items/kg. Most observed MPs were fibers (60.0% in the water; 56.0% in the sediments), followed by fragments and lines. Detected MPs were dominated by polypropylene (20.7%) in the water, and acrylic (15.4%) in the sediment, black colored (76.2% in the water, 72.7% in the sediments), and 200–500 μm sized (48% in the water, 37% in the sediments). Pollution Risk Index (PRI) indicated significant pollution levels (from medium to very high) in estuarine and coastal areas. Multi-statistical analysis indicated land-based inputs (tourists, local waste, agriculture, and industry) dominated the studied regions. The study emphasized the potential impact of MPs pollution on aquatic ecosystems, emphasizing the need for effective management, mitigation methods, continuous surveillance, and thorough evaluation.

Keyword: microplastic (MP); pollution risk assessment; polymer variety; Bay of Bengal; Karnaphuli estuary; Meghna estuary

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1 INTRODUCTION

Plastic pollution is a global issue resulting from the production of materials, inadequate waste disposal, and slow breakdown (Jing et al., 2020; Jing and Sutikno 2020; Xia et al., 2021). Approximately 4.8–12.7 million tons of plastic are released into the seas annually, accounting for 60%–80% of all marine litter (Jambeck et al., 2015; Li et al., 2023). Microplastics (MPs), smaller than 5 mm (Thompson et al., 2004; Zhang et al., 2022), is a significant environmental problem with far-reaching effects. MPs are found in soil, rivers, lakes, oceans, and the atmosphere (Browne et al., 2011; Sanchez et al., 2014; Zhao et al., 2014; Lima et al., 2015; Anderson et al., 2016; Biginagwa et al., 2016; Andrady, 2017) and their presence is of concern due to their ability to collect toxins, be consumed by marine species, move up the food chain, and endanger human health through seafood intake (Rochman et al., 2013; Wright et al., 2013; Cózar et al., 2014; Allen et al., 2019; Xia et al., 2021). MPs in the marine environment is also a significant concern. Marine creatures, from benthic invertebrates to filter-feeding species, may unintentionally absorb MPs, leading to harmful physical and toxicological effects. Consumption of MPs can alter feeding habits, impede growth, and jeopardize reproduction effectiveness. MPs can also act as carriers for pollutants, potentially introducing dangerous substances into the food chain (Rochman et al., 2013). They altered sediment characteristics caused by MPs depots affect the nutrients of MPs, cycling, sediment stability, and overall ecosystem dynamics (Horton et al., 2017). They often come from decomposing oversized plastic objects or shedding microbeads from personal care products. Once in the water, they can leak interior dangerous compounds into the marine ecosystem due to the use of potentially hazardous chemicals in plastic manufacturing (Cesa et al., 2017; Zhang et al., 2019; Gola et al., 2021; Hossain et al., 2023; Zhu et al., 2023).

The Bay of Bengal, a vast and partially confined water body, is a critical area for studying the movement and dispersion of MPs (Thompson, 2015). Its unique hydrological and oceanographic characteristics, including its terrain, currents, and circulation patterns, contribute to the movement and dispersion of MPs (Hossain et al., 2020). The region is surrounded by densely populated coastal areas, such as the Ganges-Brahmaputra Delta, contributing to increased plastic consumption and waste generation. MPs accumulation in the coastal areas of North, Northern east of the Bay of Bengal is primarily due to factors like tourist activities, agricultural pollutants, storm surges, urban centers, industrial zones, inadequate waste management practices, and limited public awareness (Napper et al., 2021; Haque et al., 2023). The Karnaphuli River in Bangladesh is a primary MPs source (Mao et al., 2021) due to improper waste disposal, inadequate waste management infrastructure, and untreated sewage discharge. The river's hydrodynamic features, particularly in densely populated urban areas, contribute to the transport and deposition of MPs. Limited awareness about plastic contamination and inadequate waste management infrastructure exacerbate the problem. The river's central industrial and commercial hub is also at risk. The Meghna River in Bangladesh is a major MPs hotspot (Napper et al., 2021) due to dense population, inadequate waste management infrastructure, agricultural and industrial runoff, and urbanization (Napper et al., 2021). The river's flow and hydrodynamic characteristics also contribute to the accumulation of MPs.

Extensive global research has shown that MPs are prevalent in several settings, such as marine, freshwater, and terrestrial ecosystems (Geyer et al., 2017). Recent studies have found increased levels of MPs in the coastal waters and sediments of the Bay of Bengal. Al Nahian et al. (2023) found MPs concentration in the water and sediment of the Moheskhali Channel of Cox's Bazar at 0–0.1 items/m^3 and 6.66–138.33 items/kg. MPs concentration were recorded as 150.00±65.62 items/m^3 and 30.56±9.34 items/kg in the Meghna estuary, and 350±69.22 items/m^3 and 102.22±40.01 items/kg in the Karnaphuli estuary (Banik et al., 2024). Studying the pollution caused by MPs in the estuary and coastal regions of the northern Bay of Bengal is highly significant because of its environmental importance and the potential harm it may cause to marine ecosystems and human health (Sarker et al., 2020). The Bay's abundant biodiversity and diverse marine habitats render it a crucial region for investigating the ecological ramifications of plastic waste. This research will establish a baseline for understanding MPs contamination in the Karnaphuli estuary, the Meghna estuary, and the southeastern coastal regions of Bangladesh. This baseline will also assist the government of Bangladesh and its neighboring countries in managing and monitoring discharge into the Bay of Bengal. The objectives of this research were to determine the spatial distribution and morphological characteristics (color, shape, polymer, and size) of MPs in sediments and surface water in the studied estuaries and coastal regions, to map the MPs polluted areas, to study the probable sources of MPs in the studied areas, and to find the risk assessments indices for surface water and sediments of the studied regions. This study developed a knowledge-based baseline scenario and long-term monitoring programs for managing MPs pollution in the Bay of Bengal, along with two central river systems (Karnaphuli and Meghna).

2 MATERIAL AND METHOD

2.1 Study area

The southeastern coasts of the Bay of Bengal in Bangladesh have a topographical makeup consisting of flat land and rivers that carry contaminants, such as MPs, from inland areas to the sea. The area lies near urban hubs such as Cox's Bazar and Chittagong, resulting in heightened pollution caused by human activity and insufficient waste disposal practices. Saint Martin Island, Cox's Bazar, Teknaf, Chittagong, Sandwip Island, and Nijhum Dwip are prominent coastal regions in Bangladesh renowned for their appeal to tourists and significant involvement in fishing endeavors. The region's abundant biodiversity, encompassing mangrove forests and coral reefs, faces a substantial threat from the contamination of MPs. The Karnaphuli River, which flows through Chittagong, the financial capital and second largest city in Bangladesh, is distinguished by its semi-daily currents and an average channel depth of 8–10 m. The river receives water from canals and tributaries, which contain waste from the industrial, commercial, residential, urban, and agricultural sectors. The river length is roughly 170 km, and the catchment area is 11 000 km^2. Water contamination occurs through farming practices, including the use of fertilizers and pesticides. Additionally, hospital garbage is released into the river. The Chittagong City Corporation discharges garbage near the river, potentially exacerbating the water quality and introducing contaminants such as MPs due to human activities, including aquaculture farming and tourism. The Meghna River's shape, water flow, wind, and ocean conditions influence its estuary. The Ganges valley connects Tibet, northeastern Bangladesh, and northeastern India (Jakobsen et al., 2002). The lower Meghna River drains these areas, with water discharge ranging from 8 000 to 120 000 m^3/s. Salinity levels vary throughout the year, with the lowest levels in August and September and the highest in March and April. Monsoon seasons bring strong winds and high water velocities (Ali, 1995). The river and its wetlands are home to diverse species, but pollution from plastic waste is a significant concern.

Seven sites from Bangladesh's southeastern coastal regions, six sites from the Karnaphuli estuary, and seven sites from the Meghna estuary were selected for water and sediment samples (Fig.1; Supplementary Table S1).

2.2 Sample collection

Water samples were obtained throughout the period spanning from November 2021 to April 2023 from coastal regions in the south-southeast, as well as from the estuaries of the Meghna and Karnaphuli River (Fig.1; Supplementary Table S1). Water samples were collected from the surface using an aluminum kettle and passed through a nylon neuston net measuring 22 cm×22 cm in pore size of 47 µm. A total volume of 200 L of water was passed through the neuston net at each sampling site. Following filtration, the neuston nets were subsequently enveloped with aluminum foil and appropriately labeled with their location, time, and temperature. The obtained water samples were stored in a chiller at a temperature of 4 °C before subsequent examination (Zhang et al., 2017). For sediments sampling, a 15-kg stainless steel Ekman grab sampler was utilized to gather sediment samples from each sampling site, explicitly targeting the material within the 0–50-cm depth range. During each sampling period, the Ekman grab sampler was meticulously cleaned using deionized water to minimize the potential for cross-contamination. The sediment samples were stored in a refrigerated container and subsequently transported to the laboratory, where they were held at -20° C for subsequent examination.

2.3 Sample pretreatment

The pretreatment protocol for water samples was the same as in our earlier research (Cai et al., 2018; Tang et al., 2018). In short, the sieves were cleaned three times for two minutes using Milli-Q water and an ultrasonic cleaning tool. The large debris (>5 mm) was screened with a 5-mm steel-wire sieve

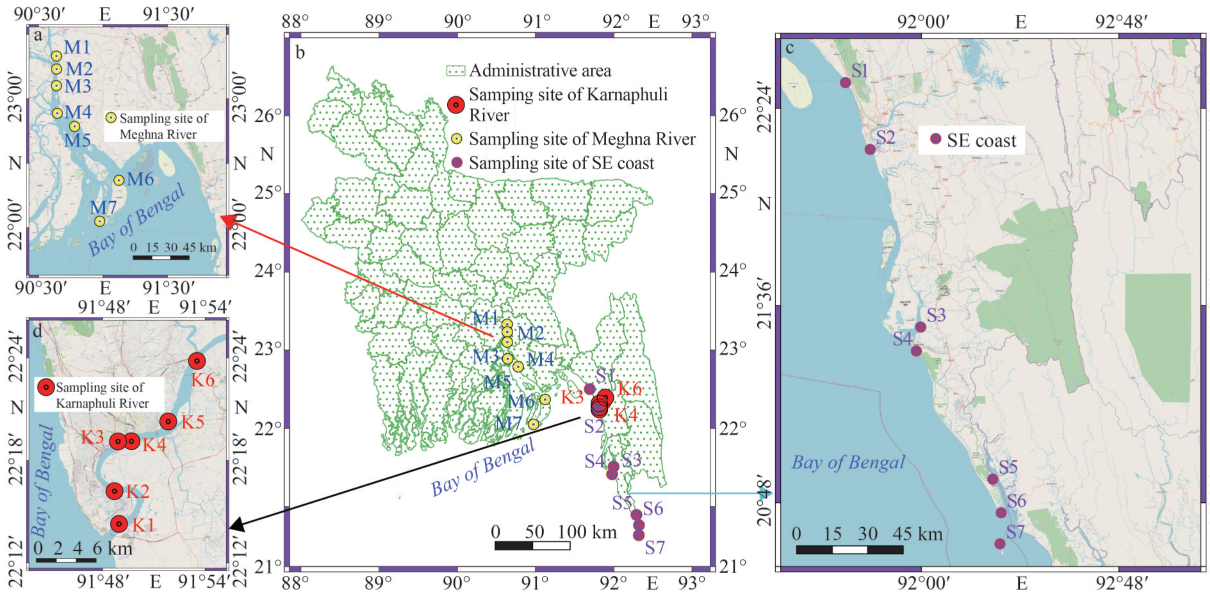

Fig.1 Sampling site

a. Meghna River estuary sampling sites; b. Bangladesh; c. sampling sites of southeastern coast; d. Karnaphuli River estuary sampling sites.

and discarded. The rest were filtered onto nylon filters (Millipore, 20 μm), and the contents on the filters were oxidatively cleaned using 30% H_2O_2 (Nuelle et al., 2014; Zhao et al., 2014). The filters' contents were washed with a 30% H_2O_2 solution before being heated to 65 °C for 24–48 h for oxidation and digestion (Nuelle et al., 2014; Zhao et al., 2014). After screening the plastic particles using density separation with a NaCl solution (1.2 g/cm^3) for 24 h (Hidalgo-Ruz et al., 2012), the supernatant was filtered through a nylon filter in pore size of 20 μm, and placed in a filter case (Petri dish) for further analysis (Millipore, USA).

The pretreatment method for sediment samples was slightly modified as per Tang et al. (2018). Initially, 800 g of sediment was weighed and placed in a 2-L pre-cleaned beaker, and dried at 65±5 °C until fully dry, and then the dry weight of the samples were measured. Subsequently, the sample was transferred to a shaker and shaken for 40–60 m (Qi et al., 2022), and then dried at 65 °C to a constant weight. Dry samples were separated using a flotation device with NaCl (1.2 g/cm^3). Afterwards, the supernatant containing MPs was digested with 30% H_2O_2 solution until completely digested (Desforges et al., 2015). Finally, the solvent was continuously filtered through a nylon filter (Millipore. Diameter 47 mm, pore size 20 μm), stored in a Petri dish, and dried at 50 °C for 24 h before further analysis (Liu et al., 2021).

2.4 Visual examination and identification

All suspected particles were visualized with a 20–40 magnification stereoscopic microscope (Dino-Lite, AM4113T (R4), Taiwan, China) and then linked to a computer so that "zigzag" mode images to taken of each spot until they were all covered. MPs characteristics, including shape, particle size, and color, were documented. The composition of the particles in reflection mode was determined using a Fourier transform infrared micro-spectroscopy (Shimadzu, IRAffinityTM-1S, AIM-9000, Japan). Ten randomly selected particles were used to represent one FTIR analysis sample. The microplastics samples were identified using micro-FTIR with the highest similarity (at least 70% similarity for confirmation) in the database (Hidalgo-Ruz et al., 2012; Cai et al., 2018). At least two distinct sections were detected for each microplastics particle during micro-FTIR identification (Martins and Sobral, 2011). The software LabSolutions™ IR was used to analyze and compare the spectra to its spectrum library. With 20 scans at a resolution of 8/cm, the spectral detector range was 7 600–450/cm (Detector MCT). The MPs' size was measured by determining the longest dimension of each particle, taking into account their irregular shapes (Sagawa et al., 2018). The counting procedure additionally encompassed the identification of MPs based on their forms and colors.

2.5 Quality assurance and quality control

To ensure the highest data quality, a strict procedure was followed. Parallel samples are collected from several sampling sites. Specifically, three laboratory blank tests (n=3) are conducted, and the mean value for the blank test is 2.33±0.58 items per beaker with polyester (fibers) characteristics. The blank values are adjusted with our sampling data. During the sampling process, all sampling devices and tools were thoroughly cleaned with Milli-Q water before use. In the pre-treatment process, all instruments and utensils were washed three times with Milli-Q water, dried, and covered with aluminum foils. All non-closed parts of the instruments (such as the funnel in the vacuum filter device) were covered with aluminum foil when not in use. This was a crucial step in preventing contamination and ensuring the integrity of the data. After microscope, inspection, and selection of the filter membrane, it was immediately covered with a membrane cap. Wearing a cotton lab coat, mask, and disposable nitrile gloves was necessary for the pre-treatment and analysis of the samples. Aluminum foil was also placed over the filtration and density separation devices while they are used to prevent contamination from the air. The filter membranes holding the extracted MPs were put inside the laser confocal FTIR spectrometer's closed hood for MP observation and detection.

2.6 Statistical analysis

MPs in surface water and sediments were identified through statistical analyses. All results for the abundance of MPs in sediment samples were expressed as the number of MPs items per kilogram of dry sediment (number of items/kg) and items/m^3 of water samples. Non-metric multidimensional scaling (NMDS), the Pearson's correlation matrix plots (PCM), and principal component analysis (PCA) were used to show the correlations and significances among variables. Other statistical analyses and figures, such as hierarchical clustering, Sankey diagrams, PCAs, and bar charts, were performed using OriginPro and Microsoft Excel 2013. Study maps were constructed by QGIS 3.14, and NMDS and PCM were established by R programming language version 4.1.0.

2.7 Assessment of ecological risk

The contamination factor (CF), pollution load index (PLI), polymer risk assessment (H), and pollution risk index (PRI) values were used in this study to determine the ecological risk of the MPs. The MPs pollution hazard level is compiled from various literature sources (Hakanson, 1980; Förstner et al., 1993; Liu et al., 2019; Rakib et al., 2022) and is presented in Table 1.

2.7.1 Contamination factor (CF)

To illustrate the level of pollution in the environment, we employed the contamination factor. Traditionally, the heavy metal content was determined by the contamination factor; however, in recent times, this technique has been used to study MPs in several publications. To determine the contamination factor, Eq.1 was used.

$$\mathrm{CF}_i = C_i / C_0, \quad (1)$$

where CF_i represented the contamination factor in a particular site, C_0 denotes the baseline concentration value and C_i denotes abundance of MPs in a particular place. The background value of the MPs was determined by using the lowest concentration from each separate method (Wang et al., 2021).

2.7.2 Pollution load index (PLI)

The MPs concentration level associated with the pollution load index (PLI) was determined using Eqs.2–3, as shown below (Wang et al., 2021).

$$\mathrm{PLI}_i = \sqrt{\mathrm{CF}_i}, \quad (2)$$

$$\mathrm{PLI}_{\mathrm{area}} = \sqrt[n]{\mathrm{CF}_1 \times \mathrm{CF}_2 \times \mathrm{CF}_3 \times \mathrm{CF}_4 \times \cdots \times \mathrm{CF}_n}, \quad (3)$$

PLI_i represented the pollution load index of a particular site; $\mathrm{PLI}_{\mathrm{area}}$ denotes the pollution load index of studied area, n denotes the total number of stations.

2.7.3 Polymer risk assessment (H)

$$H_{\mathrm{area}} = \sum (P_{ji} / C_i \times S_j), \quad (4)$$

where H_{area} denoted polymer risk index of studied area. P_{ji} represented the number of MPs polymer recorded at the i^{th} station, C_i represented MPs abundance in i^{th} station, and S_j denoted the chemical toxicity coefficients or hazard score of polymers.

2.7.4 Pollution risk assessment (PRI)

$$\mathrm{PRI}_i = \mathrm{H}_i \times \mathrm{CF}_i, \quad (5)$$

$$\mathrm{PRI}_{\mathrm{area}} = (\mathrm{PRI}_1 \times \mathrm{PRI}_2 \times \mathrm{PRI}_3 \times \cdots \times \mathrm{PRI}_n)^{1/n}, \quad (6)$$

where PRI_i denoted pollution risk index of i^{th} site, H_i represented polymeric risk index of i^{th} site, and CF_i

Table 1 Category engaged in the MPs risk assessment on rivers' estuary and coastal area

Risk assessment	Value	Risk category	Reference
Contamination factor (CF)	Less than 1	Low	Wang et al., 2021; Rakib et al., 2022; Förstner et al., 1993
	1–3	Moderate	
	2–6	High	
	>6	Very high	
Pollution load index	<10; 10–20; 20–30; >30	I, II, III, IV (polluted)	Wang et al., 2021
Polymer risk assessment (*H*)	<10	I	Rakib et al., 2020; Hakanson, 1980
	10–100	II	
	101–1000	III	
	1001–10 000	IV	
	>10 000	V	
Pollution risk index (PRI)	<150	Low	Rakib et al., 2020
	150–300	Medium	
	300–600	Considerable	
	600–1200	High	
	>1200	Very high	

denoted contamination factor of i^{th} site, and PRI_{area} represented the pollution risk index of the studied area.

3 RESULT AND DISCUSSION

3.1 MPs abundance in water

This study showed the average concentration of MPs in the surface water was 559.5±401.14 items/m^3, ranging from 105±324.47 items/m^3 to 1 640±462.57 items/m^3. Based on the data, the mean abundance of particles in water samples collected from the Karnaphuli estuary was 916.7±462.6 items/m^3, from the Meghna estuary was 462.9±324.5 items/m^3, and from the southern east coastal region was 350.0±190.5 items/m^3 (Fig.2a–c). The water samples at K6 (Kalurghat Bride, Karnaphuli River) had the highest microplastics concentration at 1 640±462.57 items/m^3, followed by K3 (1 185±462.57 items/m^3), M2 (1 035±324.47 items/m^3), and K4 (1 025±462.57 items/m^3). In contrast, M7 (Nijhum Dwip) had the lowest concentration at 105±324.47 items/m^3. Compared to other rivers throughout the world, such as the Nakdong River, Korea (4 760±5 242 items/m^3), Antua River, Portugal (2.6–629 items/m^3), the Vistula River, Poland (1 600–2 550 items/m^3), the number of MPs in surface water was significantly lower (Rodrigues et al., 2018; Eo et al., 2019; Sekudewicz et al., 2021). The concentration value was relatively high when compared to other rivers around the world, like the Puducherry coast in India (1.25±0.88 items/m^3) (Dowarah and Devipriya, 2019), and Laguna de Bay, Philippines (14.29 items/m^3) (Arcadio et al., 2023). A similar finding ((570±0.1)–(6 630±0.5) items/m^3) was done by Hossain et al. (2022a) in the Karnaphuli estuary (Table 2). Approximately 750 companies directly or indirectly release untreated sewage or wastewater into the Karnaphuli River. About 160 of those companies are along the river. The Chittagong City Corporation has been offloading urban waste in many areas near the Karnaphuli River, which may be the reason for the elevated levels of MPs. According to SEHD (1998), the daily total solid waste rate was around 760 tons. On the other hand, in 2018, Chittagong City Corporation generated 2 289 tons of solid garbage per day from residential, commercial, industrial, and market sources; 8.3% of the waste consisted of plastic goods (Van De Mheen et al., 1998; Masum et al., 2021). Most trash is not recycled, and only a tiny portion of rubbish is recycled sufficiently (Masum et al., 2021). Along the Karnaphuli River bank, fishing nets that were broken or no longer functioning, as well as other fishing gear such as fish baskets and bags, ropes, and floats, were being disposed of, which may be another factor contributing to the increased levels of MPs. Approximately 1 700 boats pass through Chittagong Port every year; paint degradation from these vessels can form MPs.

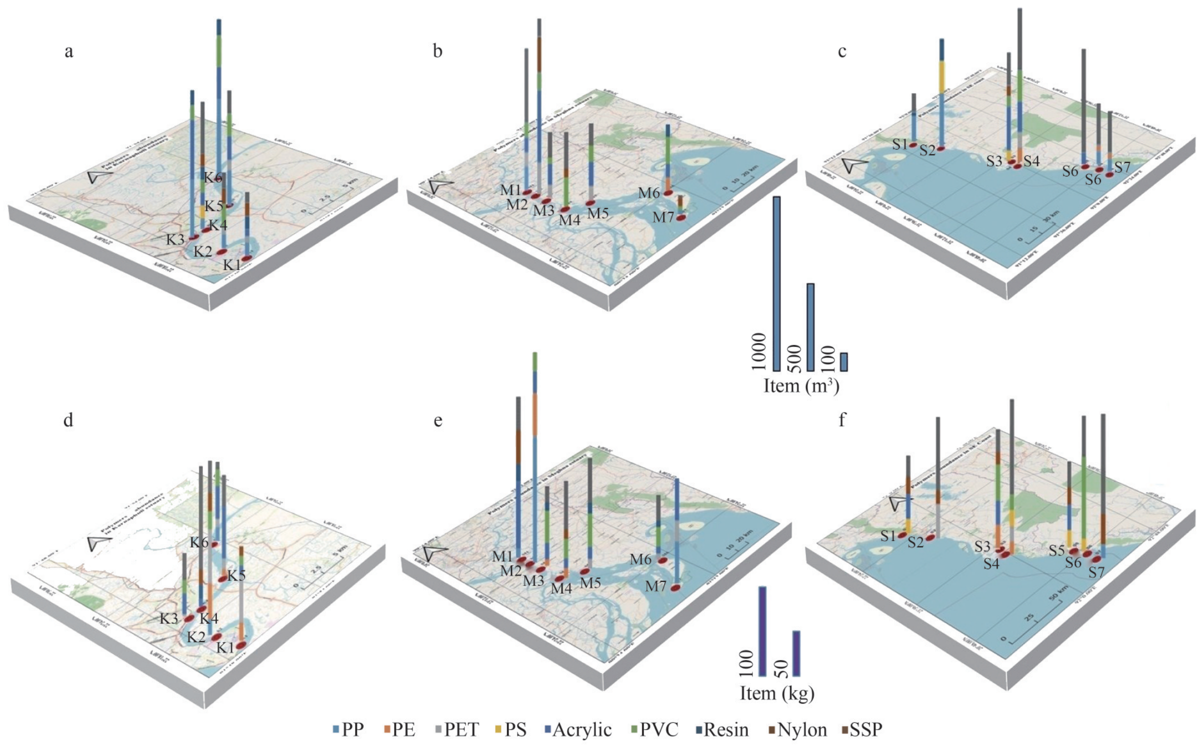

Fig.2 MPs abundance and characteristics in water and sediments of different areas

In water: a. Karnaphuli estuary; b. Meghna estuary; c. southeastern coast: in sediment; d. Karnaphuli estuary; e. Meghna estuary; f. southeastern coast.

Table 2 Comparative abundance of MPs in river/coastal channels worldwide

Region	Abundance (units: items/m^3 for waters and items/kg for sediments)	Reference
Surface water		
Nakdong River, Korea	4 760±5 242	Eo et al., 2019
Antua River, Portugal	2.6–629	Rodrigues et al., 2018
Vistula River, Poland	1 600–2 550	Sekudewicz et al., 2021
Puducherry coast in India	1.25±0.88	Dowarah and Devipriya, 2019
Laguna de Bay, Philippines	14.29	Arcadio et al., 2023
Karnaphuli estuary, Bangladesh	(570±0.1)–(6 630±0.5)	Hossain et al., 2022a
This study	**559.5±401.14**	
Sediment		
Amazon River, Brazil	417–8 178	Gerolin et al., 2020
Zhujiang River, China	80–9 597	Lin et al., 2018
Changjiang estuary, China	121	Peng et al., 2017
Turag River, Bangladesh	86±12.2	Hossain et al., 2022b
Cox's Bazar beach, Bangladesh	8.1±2.9	Rahman et al., 2020
This study	**130.43±62.86**	

Moreover, trawlers, mechanized boats, fishing boats, and river crafts can all be a part of the plastic pollution in the Karnaphuli River. Additional factors contributing to plastics in the Karnaphuli River include human activities such as aquaculture farming and tourism near the river bank. On the other hand, at point M7 (Nijhum Dwip), a small island (163.52 km^2) of mangrove forest biome raised on the estuary of the great Meghna channel in the mouth of the Bay of Bengal has the lowest concentration of MPs due to less shipping activities, less anthropogenic activities, less agricultural and commercial activities. Comparing the results with those of other studies remains problematic due to the lack of a single, universal standard monitoring method for MPs in marine environments, as well as methodological diversity in the sampling, sample preparation, and MPs identification processes (Van Cauwenberghe et al., 2014; Wang et al., 2018; Mehdinia et al., 2020).

The highest concentration of MPs in the Karnaphuli estuary (at K6) can be attributed to its proximity to Chittagong, a heavily industrialized and densely populated city with poor waste management practices, extensive human activities, and lax environmental regulation enforcement.

3.2 MPs abundance in sediments

The sediment samples exhibited an average concentration of 130.4±62.9 items/kg of MPs items, varied from 60.0±33.1 items/kg to 334.3±89.0 items/kg. Based on the results, the abundance of MPs in sediment in the Karnaphuli estuary was 94.3±33.1 items/kg, in the Meghna estuary was 157.6±89.0 items/kg, and in the southeastern coastal region was 134.3±38.7 items/kg (Fig.2d–f). The MPs concentration in sediment samples at M2 (Boro Station, Meghna River, Chandpur) was the highest at 334.3±89.0 items/kg and lowest at 60±33.1 items/kg at K3 (Fig.2; Supplementary Fig.S1) (Bangla Bazar Jetty).

Due to growing industrial and everyday human activities in the area, site M2 (Borostation, Meghna River, Chandpur) and M1 (Amirabad ferry terminal) have relatively higher concentrations of MPs than other sites. It may be due to extensive fishing activities, water transportation activities/shipping, anthropogenic contamination, untreated garbage management, agricultural and commercial land use contamination, fish market-based plastics usage, and tourism activities. The sediment sample average concentration was notably lower than that of the Amazon River (417–8 178 items/kg) (Gerolin et al., 2020), Zhujiang (Pearl) River (80–9 597 items/kg) (Lin et al., 2018), and relatively higher than that of other rivers, including Changjiang (Yangtze) River estuary, China (121 items/kg) (Peng et al., 2017), Turag River (86±12.2 items/kg) (Hossain et al., 2022b), Cox's Bazar beach (8.1±2.9 items/kg) (Rahman et al., 2020) (Table 2).

The lower concentration of MPs in the sediment at the Karnaphuli estuary compared to the Meghna estuary and the southeastern coast of Bangladesh may be attributed to the hydrodynamic characteristics of each region. The higher water flow and more pronounced tidal actions in the Karnaphuli estuary likely lead to the efficient dispersion of MPs into the water column, minimizing their settlement in the sediment. Conversely, the Meghna estuary and southeastern coast may exhibit sedimentary conditions and local hydrodynamics that favor the retention and accumulation of MPs in the sediment. Further research into these areas' specific sediment compositions and hydrodynamic regimes is warranted to understand better the mechanisms driving microplastic distribution and accumulation in estuarine environments.

3.3 Variations in shape, color, and size

Our study found six distinct shapes of MPs particles in water and sediment from studied area predominated by fibers (60%) followed by fragments (33%), lines (7%), while the least common type were films, foams, and pellets (less than 1%) (Fig.3a). Fibers was the most abundant type of MPs found in sediment samples, accounting for 56% of the total, while films, foams, and pellets were the least abundant (less than 1%) (Fig.4a).

A total of seven distinct colors of MPs were found in the samples collected, namely black, white, red, blue, yellow, green, and transparent (Figs.3b & 4b). Based on the data presented in Figs.3b & 4b, it can be observed that the predominant color type in the water was black, accounting for 72.35% of the total and in the sediment was black accounting for 72.7% followed by white, accounting for 5.15% (Supplementary Fig.S2).

The primary size water's range of MPs was 200–500 μm, accounting for 48% of the total. Other size categories were 500–1 000 μm (26%), 1 000–5 000 μm (19%), and 0–200 mm (7%) (Fig.3c). The sediment size distribution was varying from 200–500 μm accounted for 37% of the total, followed by 500–1 000 μm (27%), 1 000–5 000 μm (27%), and >200 μm (9%) (Fig.4c; Supplementary Fig.S2).

3.4 Variation of polymers

The chemical composition of the MPs particles was determined using Fourier Transform Infrared Spectroscopy (FTIR). FTIR analysis revealed the presence of nine distinct polymers in the water samples. The particles that were obtained had a chemical composition consisting of semi synthetic polymer (SSP) 24% (Cellulose at a proportion of

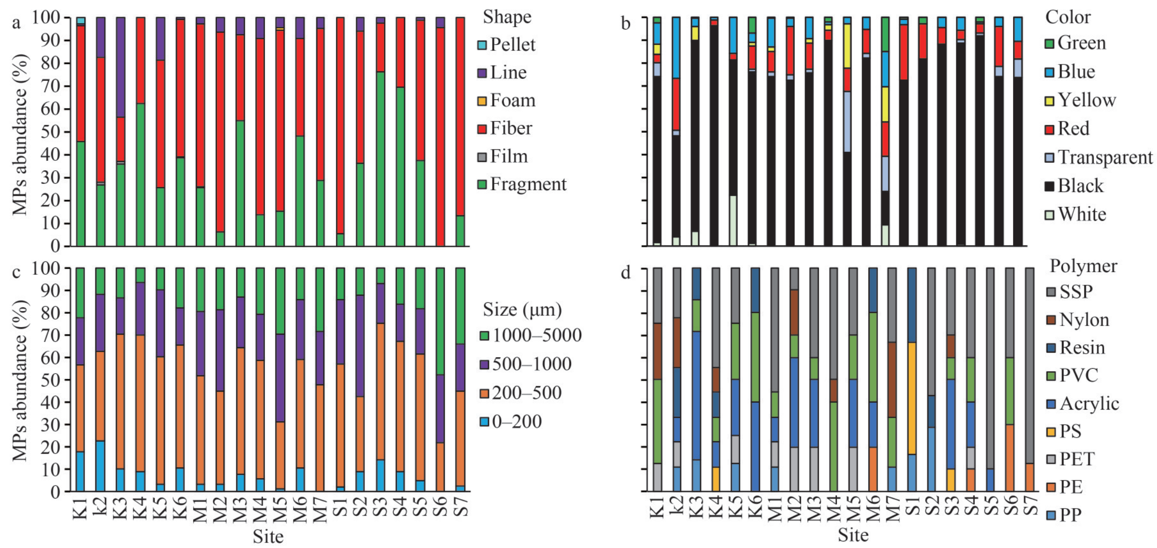

Fig.3 Pollution characteristics of MPs in water

a. shape; b. color; c. size; d. polymer.

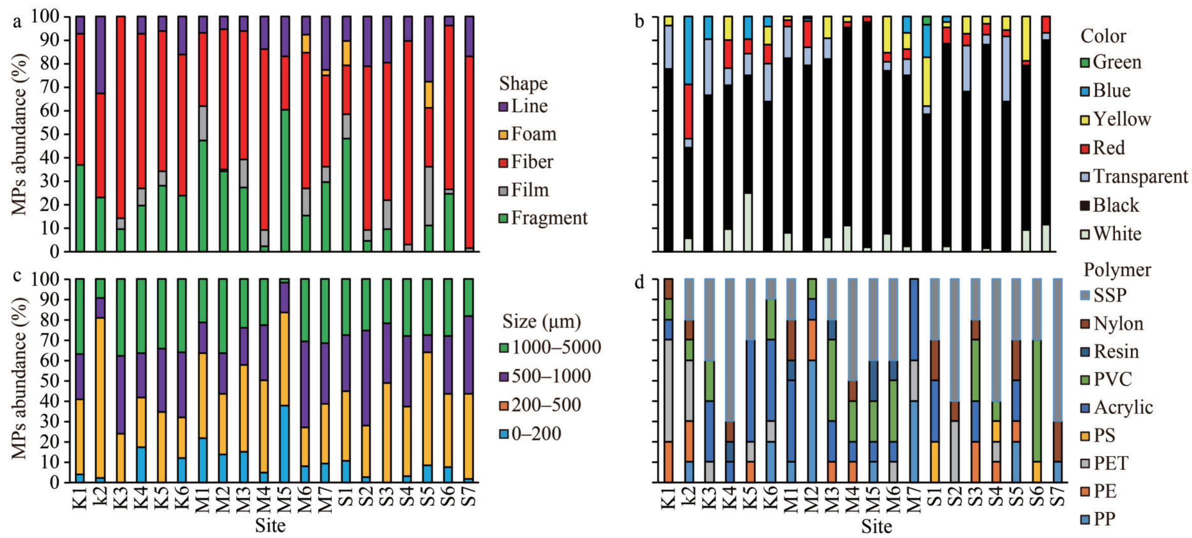

Fig.4 Pollution characteristics of MPs in sediment

a. shape; b. color; c. size; d. polymer.

13.1%, cotton 7.1%, and rayon 4.4%) along with polypropylene (PP) 20.72% (included combination of polypropylene and polyethylene (PP. PE) 3.5%), acrylic 19.3%, polyvinyl chloride (PVC) 14.7%, nylon 5.5%, resin 5.6%, polyethylene (PE) 1.5%, polyethylene terephthalate (PET) 5.7% (included polyethersulfone (PES) 2.2%), and polystyrene (PS) 2.5%. A comprehensive analysis of the sediment sample revealed the presence of nine distinct polymers, as determined by FTIR spectroscopy. The chemical composition of the obtained particle consisted of acrylic (15.4%), SSP 31% (included Cellulose 14.2%, cotton 10.3%, and rayon 6.5%), PVC (12.8%), PP 13.7% (included PP. PE 2%), nylon (7%), PE (7.5%), PET 7.8% (included PES 4.7%), resin (3%), and PS (1.8%).

3.5 Pearson's correlation matrix (PCM) and non-multidimensional scaling (NMDS) analysis

Pearson's correlation matrix (PCM) was designed to ascertain the strength of correlations between the various factors under investigation (Fig.5). A moderate level of correlation is indicated by an absolute value between 0.5 and 0.7. A total value of greater than 0.7 indicates a high correlation. Fragments had a moderate correlation with PP, acrylic, PVC, and resin, and fibers had a significant correlation with PVC and a moderate correlation with PP, PET, PVC, and acrylic. Lines had a moderate correlation with acrylic. Nevertheless, films had no significant, moderate, or high correlation with any polymers. The study investigates the spatial distribution of MPs in the Karnaphuli estuary, the Meghna estuary, and the southeastern coastal region of Bangladesh, revealing variations in concentration levels between water and sediment (Fig.6).

The number of MPs typologies found in water and sediment samples was used to create a non-metric multidimensional scaling plot for identifying MPs with different shapes and polymers in sediment and water samples collected from various locations. The Bray-Curtis dissimilarity metric was employed and plotted in two dimensions. Plotting samples spatially adjacent indicates that their MPs composition is more comparable. As previously noted by Kooi et al. (2019) and Reisser et al. (2015), the concentration of MPs in the water samples was higher than in the sediment samples, similar to this study. Higher concentrations of MPs in the water compared to the sediment in estuarine and coastal regions are primarily due to turbulent hydrodynamic conditions, biofouling, sediment resuspension in the water column, and the lower density of many MPs, which prevent them from settling. Continuous surface runoff and river discharge inputs also may contribute to higher water concentrations.

Furthermore, the preponderance of distinct MPs types distinguished the marine layers (water and sediment). The NMDS analysis revealed a higher fiber abundance in sediment samples, indicating a more robust particle sinking capacity. Even though we utilized two unique sampling strategies, which might have a detrimental influence on how comparable the data are, and our results are remarkably similar to those of Kooi et al. (2019) and Reisser et al. (2015). In fact, because of their great buoyancy, plastic spheres, and product fragments frequently dominated the surface water in terms of numbers (Chubarenko et al., 2016). On the other hand, the leading causes of plastic contamination on the seafloor are fragments and fibers. This might be caused by the high densities of various polymers (such as polyesters; Woodall et al., 2014) used in the textile industry. Fibers also have a high surface-area-to-volume ratio, making them vulnerable to biofouling and lowering their buoyancy (Fischer et al., 2022). SSP, nylon, PVC, acrylic, and PE were found in both water and sediment samples in the studied regions. Nylon, a polyamide-derived synthetic polymer, is known for its high strength, durability, excellent abrasion resistance, good chemical resistance, and flexibility. It is widely used in textiles, carpets, and ropes. Nylon is also used in

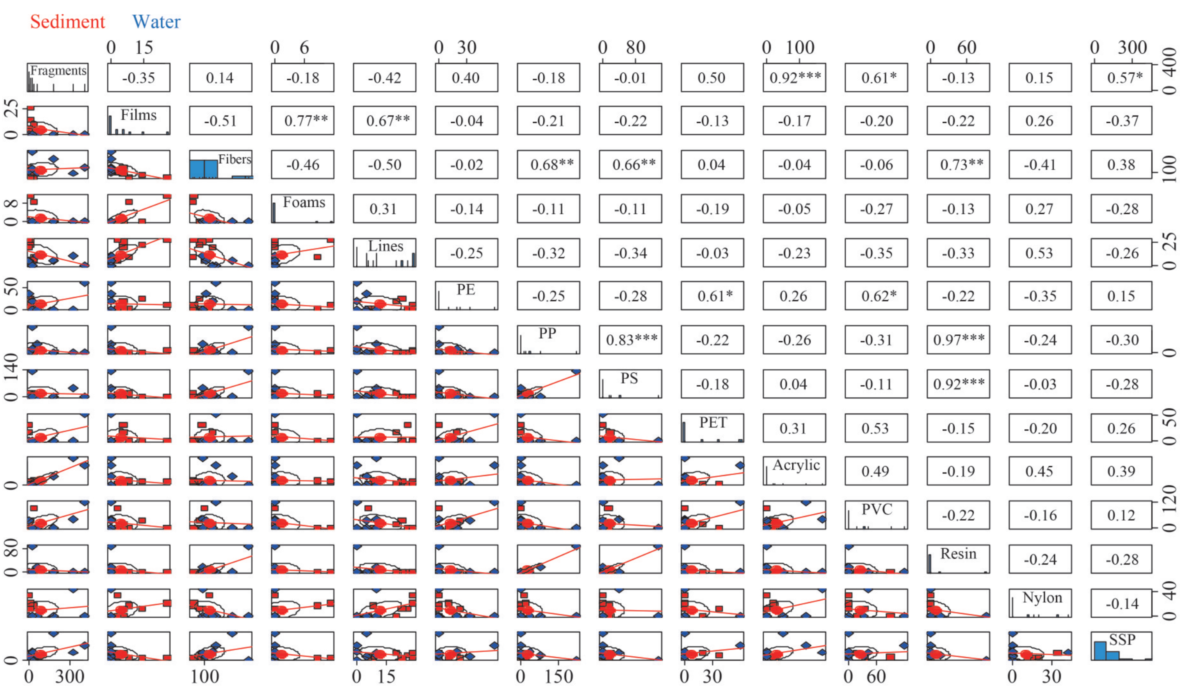

Fig.5 The Pearson's correlation analysis of shapes and polymers between water and sediment

Significance level -0.001 (***); 0.01 (**); 0.05 (*).

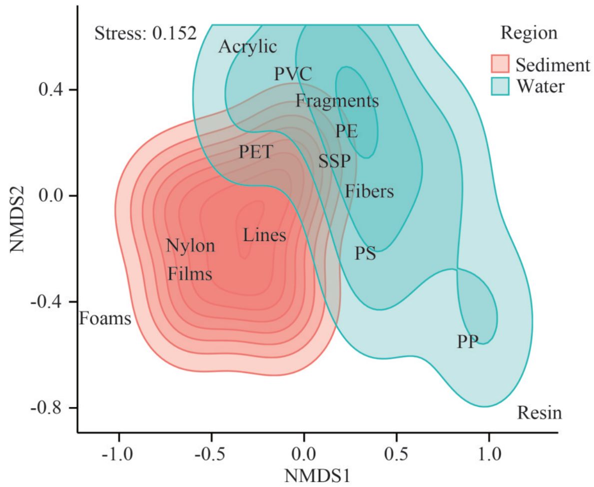

Fig.6 Non-metric multidimensional scaling analysis of shapes and polymers between water and sediment

fishing nets for its softness, lightness, elastic recovery, stretch ability, high abrasion, and temperature resistance (Thomas and Sandhya, 2019).

Almost all stations in the Meghna estuary and southeastern coastal regions are subjected to marine fishing activities. Acrylic, a lightweight, transparent, and weather-resistant synthetic polymer, is commonly used in signage, furniture, paints, and various consumer goods due to its excellent impact strength. Sampling sites with an abundance of acrylic in both sediments and waters are highly exposed or adjacent to shipbuilding industries, in Chittagong (in the Karnaphuli estuary and downstream estuary of the Meghna River), furniture trading, which uses enormous quantities of different types of paints. NMDS scaling analysis found PVC, a versatile, durable, and long-lasting synthetic polymer derived from vinyl chloride monomers in both water and sediment samples due to its vast uses in pipes, cables, clothing, and construction materials (Fig.6). PET was also found in both sediment and water in the studied areas due to its vast usages in various industries, including plastic bottles, food packaging, textiles, packing containers, jars, thermoformed trays, and medical devices and equipment due to its beneficial properties (Andrady et al., 2011; Andrady, 2015; Geyer et al., 2017). SSP included cellulose, cotton, and rayon, a substance created from a combination of natural polymers and synthetic additives that can contaminate water systems due to industrial discharges, incorrect waste disposal, and runoff (Galloway et al., 2017). Semi-synthetic materials can undergo degradation, releasing MPs, and contributing to their presence in water and sediment (Geyer et al., 2017). However, the stress score of 0.152, indicating a moderate fit, emphasizes the reliability of the NMDS model in preserving the original dissimilarities among MPs samples.

3.6 Probable source of MPs in the marine environment

Utilizing principal component analysis (PCA) to determine the prevalence of MPs may be more comprehensible due to the varying proportions of different plastic varieties at different sample locations. The principal component analyses (PCAs) of 20 distinct MPs defined their distributions in the water and sediment of the studied areas (Figs. 7a & 8a). The PCAs of these MPs from each sampling site revealed substantial differences. According to the findings, various MPs' morphologies predominated at different sampling locations in the study area. Fragments, fibers, films, foams, lines, pellets, and froth, which are prevalent in the surface water and sediments of numerous sampling locations along the estuarine and coastal areas, have made substantial contributions: 30.06% to the first principal component (PC1), and 16.14% to the second principal component analysis for the surface water of the studied area (Fig.7a).

PC1 presented 21.48%, and PC2 explained 20.67% of the contributions of variables in sediments (Fig.8a). In contrast to the first component (PC1), which primarily originates from activities such as fishing, farming, household, and industrial sectors, the second component (PC2) emphasized the dominance of films, fragments, pellets, and fibers in water and sediments. As indicated by distribution characteristics, agricultural activities are thus the principal source of films in the estuary. In other studies, conducted on freshwater ecosystems, the findings from the Karnaphuli estuary identified foams, films, fragments, and pellets as the principal sources of MPs in that estuary. Additionally, regional attributes, such as fishing, agriculture, effluent treatment, and so forth, are intricately linked to the distribution characteristics of distinct MPs shapes.

Hierarchical cluster analysis (Figs.7b & 8b) revealed that there were similarities in MPs concentration of fragments, fibers, and lines as shape, red as the color, PP, PVC, and resin as the polymers of sizes 0–200 μm, 200–500 μm, and 1 000–5 000 μm for both water and sediment samples. Other variables had made clusters for the

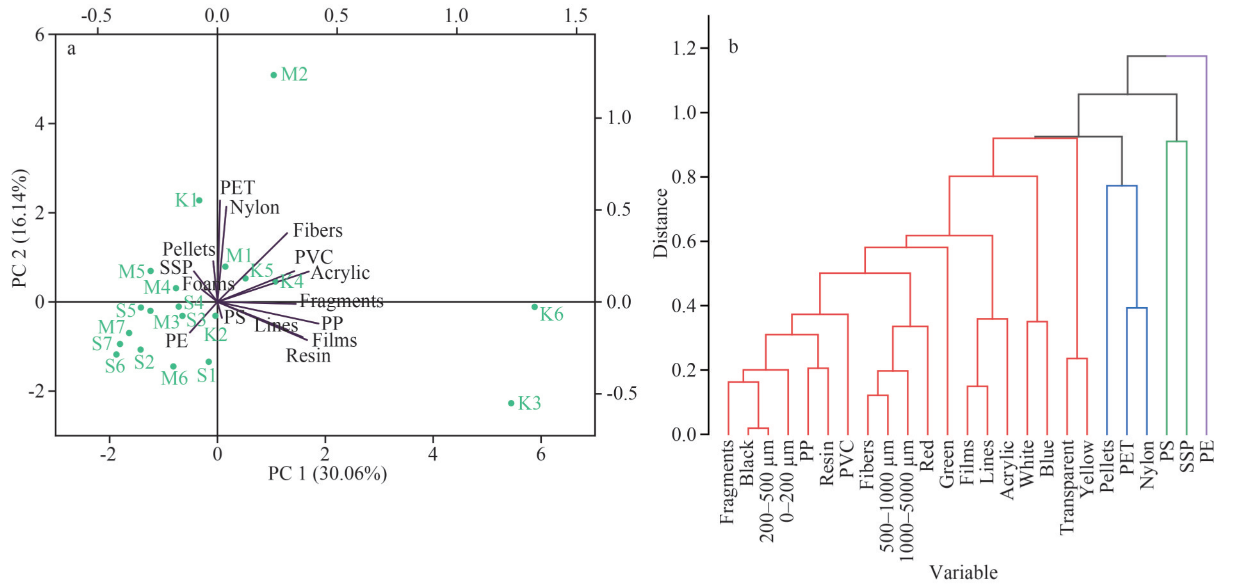

Fig.7 Principal component analysis (PCA) based on shapes and polymers of MPs (a), and hierarchical cluster analysis of various shapes, sizes, colors and polymers with respect to sampling sites in water of estuaries and southeastern coast of Bangladesh (b)

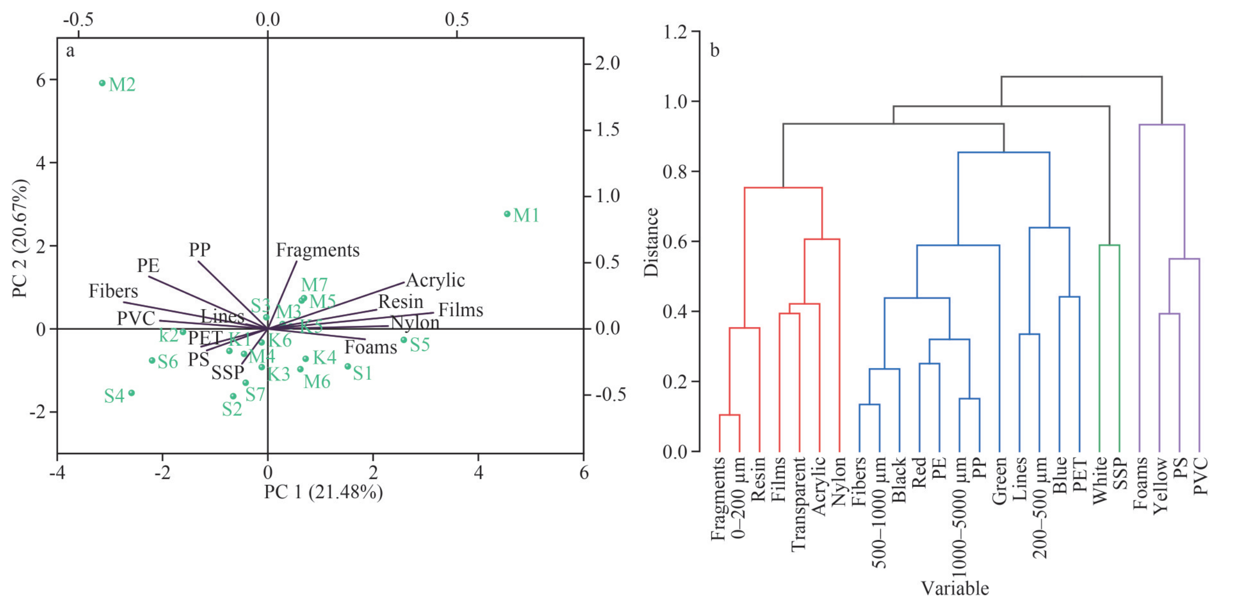

Fig.8 Principal component analysis (PCA) based on shapes and polymers of MPs (a), and hierarchical cluster analysis of various shapes, sizes, color and polymers with respect to sampling sites in sediments of estuaries and southeastern coast of Bangladesh (b)

water and sediment, which were not similar. Industries in Bangladesh, especially those producing plastics, release wastewater with PP, PVC, and resin particles into rivers such as the Karnaphuli and the Meghna, causing contamination (Rahman et al., 2020). Insufficient waste management systems in cities lead to incorrect material disposal, accumulating in storm water runoff. Agricultural practices (utilizing PVC pipes for irrigation) are also a source of plastic pollution (Hossain and Hossain, 2018). The southeastern coast of Bangladesh is a center for shipping and marine trade, where plastic goods from packing, transport, and fishing activities are often disposed of in the water due to accidents or intentional dumping. The tourism industry contributes to coastal water contamination by generating plastic garbage (Bhuiyan et al., 2017).

Chittagong and Dhaka, located along the banks of the Karnaphuli and Meghna rivers, are important hubs of industrial activity and urban development. Due to industrial production, commercial operations, and high population densities, these areas produce significant amounts of plastic garbage. Urban regions with high population density and fast urbanization lead to higher plastic usage and inadequate waste management techniques (Islam et al., 2019). The lush plains of the Karnaphuli and Meghna Rivers facilitate extensive agricultural operations. Plastic mulching films, irrigation pipes, and fertilizer bags used in agriculture can transfer MPs into water bodies via runoff. Agriculture is a predominant occupation for many people living in rural areas near these rivers. Small-scale farmers may need to gain the knowledge or means to dispose of garbage properly, resulting in the chaotic dumping of plastic items (Soares et al., 2020). The southeastern coast of Bangladesh, specifically Cox's Bazar and Saint Martin's Island, is a popular tourist destination and provides livelihoods for fishing communities. Tourism and fishing activities lead to the production of plastic garbage in coastal areas. Coastal communities depend on fishing and tourism for their sustenance. There needs to be more waste management infrastructure and awareness among inhabitants and tourists, leading to plastic pollution in coastal waters (Bhuiyan et al., 2019). The Karnaphuli estuary is an important port for Chittagong, supporting international trade and shipping operations. The ports and shipyards on the southeastern coast play a vital role in marine trade and industrial activities. Shipping activities in port towns and coastal communities lead to introducing MPs into marine habitats due to accidental spills, vessel maintenance, and cargo handling (Bhuiyan et al., 2019). Bangladesh's vast river systems, such as the Karnaphuli and Meghna Rivers, contributed to transporting plastic waste from locations further upstream. During the monsoon season, flooding worsens the movement of plastic trash from inland regions to rivers and eventually to coastal locations, leading to a higher buildup of MPs (Islam et al., 2019). During the monsoon season, flooding worsens the movement of plastic trash from inland regions to rivers and eventually to coastal locations, leading to a higher buildup of MPs (Islam et al., 2019).

Based on the above functional areas, the geographic and demographic characteristics of the Sankey diagram were formed by Origin Pro software (Fig.9). It resulted in the most dominant source region being the Karnaphuli River (35.31%), followed by the Meghna River and the coastal areas. Among the probable sources, MPs contribution is from transportation (21.13%), tourist (15.94%), local waste (14.08%), and fishing (11.27%), agriculture (8.45%), industry (8.45%), and so on.

3.7 Ecological risk assessment

A comprehensive risk assessment was conducted to understand the environmental dangers associated with MPs, using four indicators: contamination factor (CF), pollution load index (PLI), polymer risk index (*H*), and pollution risk index (PRI). The study found that all four pollution indicators demonstrated elevated contamination, potentially generating ecological risks within rivers and coastal ecosystems. The contamination factor ranged 3.57–15.6 for water samples of the Karnaphuli estuary, 2.52–9.86 for the Meghna estuary, and 1.00–5.77 for the southeastern coastal region. The PLI of water of the Karnaphuli estuary was high (2.79), medium for the Meghna estuary (1.88), and the southeastern coastal region (1.69). The average PLI of the water in the study areas was high (2.04). At the same time, PLI for the sediments of the Karnaphuli estuary, the Meghna estuary, and the southeastern coastal regions were medium (1.22, 1.53, and 1.46). The average PLI of the sediment samples of this study area was medium (1.41) (Fig.10; Supplementary Fig. S3). Alam et al. (2023) found the pollution load index of 1.86 for their study of the water of the Ganges River Basin to Meghna estuary, which also indicated the medium level of pollution load. Similarly, the Karnaphuli estuary had a PLI of 1.73 (medium level) by Rakib et al. (2022), and 1.67 in the water of Moheskhali Channel, part of the southeastern coastal region by Al Nahian et al. (2023). These PLI values are indicator to the potential impact of MPs on the water systems of our study. Polymers like polystyrene, polyamide, and acrylic have the potential to undergo degradation, resulting in the release or generation of harmful substances.

However, the *H* value in water of the Karnaphuli and the Meghna estuary fell into Category IV, followed by the coastal region in Category III (Fig.10b). *H* in the sediment of the Karnaphuli estuary and the southeastern coastal region was in Category II, and the Meghna estuary was in Category III (Fig.10e). This investigation found that the PRI for the water of the Karnaphuli estuary and Meghna estuary was very high, followed by the

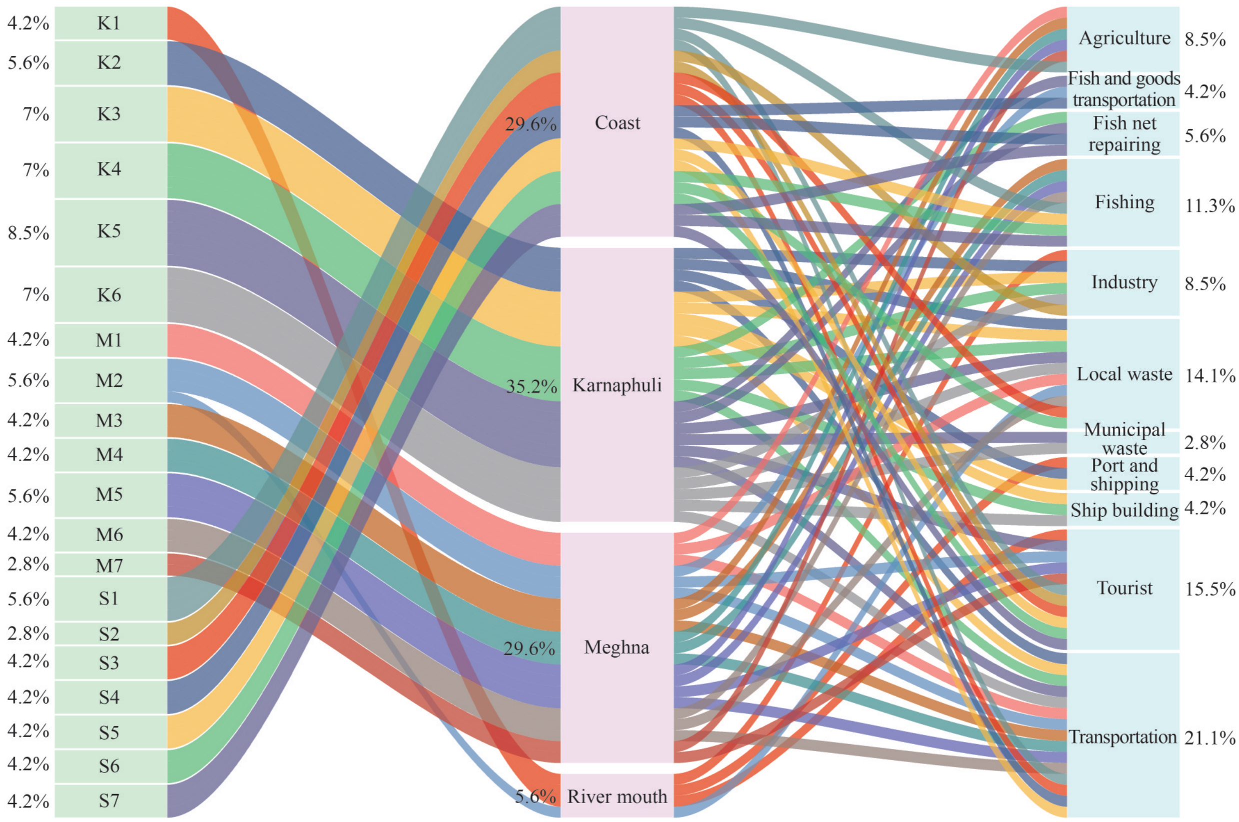

Fig.9 Sankey diagram of probable sources of MPs in the studied area

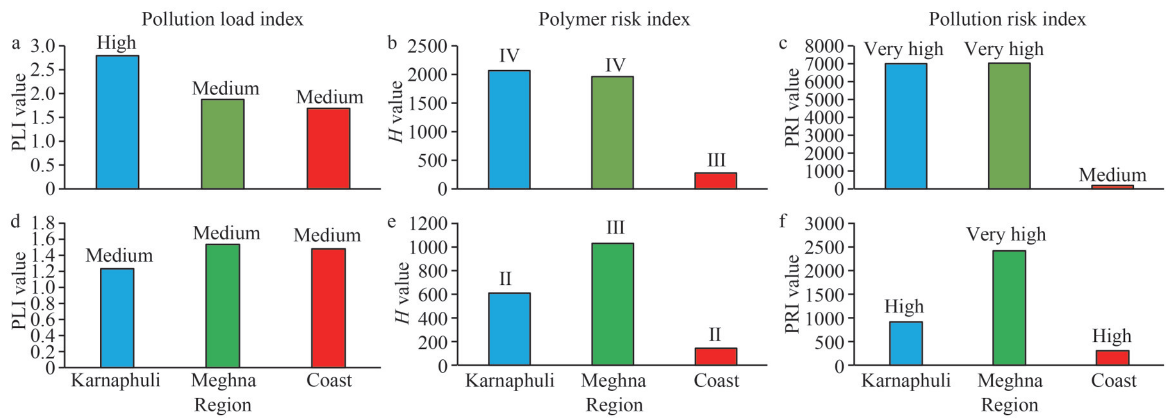

Fig.10 Risk assessments using pollution load index (a & d), polymeric risk assessment (b & e), and pollution risk assessment (c & f) in surface water & and sediment, respectively

southeastern coast in the medium category of PRI (Fig.10c). In contrast, the sediment of the Meghna estuary indicated very high category of PRI, followed by the Karnaphuli estuary and the southeastern coastal region at a level of high category (Fig.10f). PRI provides valuable insights into the potential dangers associated with specific polymers. The PRI for water and sediment samples underscores the urgent need for environmental management. The significantly elevated PRI in the Karnaphuli and Meghna estuaries serve as a good indicator to the precarious condition of these aquatic ecosystems. The analysis of sediment samples from the Meghna estuary and the southeastern coastal region revealed significant levels of risk, emphasizing the potential detrimental impacts on marine ecosystems. The comprehensive risk assessment on MPs using contamination, PLI, *H*, and PRI highlighted elevated contamination levels in water and sediments, posing ecological risks to rivers and coastal ecosystems. The Karnaphuli and Meghna estuaries exhibited very high pollution risk indices in water, underlining the crucial need for immediate and effective environmental management interventions. Sediment analysis underscores significant risks in the Meghna estuary and southeastern coastal region, emphasizing the potential harm to marine ecosystems.

4 CONCLUSION

Having investigated the distribution, sources, and ecological risks of MPs in the surface water and sediments of the southeastern coast (northeastern coastal area of the Bay of Bengal) and two principal rivers' estuaries in Bangladesh destined for the sea, the average abundance of MPs in the water and sediment were determined to be 559.5±401.14 items/m^3 and 130.43±62.86 items/kg, respectively. Most of the MPs were fibers and fragments, black and white in color, 200–500 µm in size, and acrylic and PP in composition. Among the probable sources, MPs contribution is from transportation (21.13%), tourist (15.94%), local waste (14.08%), and fishing (11.27%), agriculture (8.45%), industry (8.45%), and so on. Additions of these percentages of four land-based sources made amount of 47% (round figure). The ecological risk assessment indicated by the PLI, *H*, and PRI suggested that MPs contamination presented various ecological risks to all estuarine and coastal areas in mainly medium to very high levels of MPs contamination. This study suggested further research should highlight comprehensive management strategies to mitigate microplastics contamination in these vulnerable coastal and estuarine ecosystems.

5 DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

6 ACKNOWLEDGMENT

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Electronic supplementary material

Supplementary material (Supplementary Table S1 and Figs.S1–S3) is available in the online version of this article at https://doi.org/10.1007/s00343-024-4098-5.