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RESEARCH

Microplastics and mesoplastics in surface water, beach sediment, and crude salt from the northern Bay of Bengal, Bangladesh coast

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Abstract
Marine plastic debris is extensively documented as a worldwide ecological issue. This study elucidated the quantity and distribution of plastic items in surface water at Moheshkhali Channel, sandy beaches (Laboni beach and Crab beach), and salt beds at Moheshkhali Island from the Cox's Bazar coast of the northern Bay of Bengal, Bangladesh in Asia. The mean concentrations of microplastics (< 5 mm) in surface water, beach sediments, and crude salt were recorded to be 0.021–0.023 items/m^2, 41.00–140.60 items/m^2, and 490–630 items/kg, respectively. However, the mean concentrations of mesoplastics (5–25 mm) in surface water, beach sediments, and crude salt were recorded to be 0.004–0.006 items/m^2, 14.00–43.20 items/m^2, and 5–9 items/kg, respectively. The abundance of plastics in surface water was higher in early summer than in winter. In the case of beach sediments and crude salt, plastics abundance was higher in late monsoon and early summer, respectively. Furthermore, numerous microplastics have been found in the crude salt of Cox's Bazar coast, suggesting the possibility of ingesting such particles through food. Besides, six different types of plastics (fragment, film, fiber, foam, pellet, and microbead) were recorded, and positive correlations were found between mesoplastic and microplastic debris size classes. Fourier Transform Infrared spectroscopy was used to identify the plastic polymer types (> 300 µm items). Polyethylene (28–31%), polypropylene (25–28%), polystyrene (13–18%), and polyethylene terephthalate (12–15%) were the most common polymers in Cox's Bazar Coast of the northern Bay of Bengal that may arise from coastal tourism activities and riverine inputs. Detailed and long-term investigations are necessary to comprehend, monitor, and avoid further plastic contamination in this coastal region.

Keywords Plastic pollution · Spatial–temporal distribution · Marine ecosystem · Plastic transport · South Asia

1 Introduction

Plastics encompass the majority of marine debris, which has been identified as a severe pollutant in both marine and freshwater ecosystems (Cole et al., 2011; Dris et al., 2015; Fatema et al., 2022; Thompson et al., 2004; Wagner et al., 2014). Plastics are monomers based on polymerization with unique physicochemical characteristics and a stable structure that may persevere for hundreds of years in the environment (Jiang et al., 2018). The plastic polymer's primary ingredients are cellulose, coal, salt, natural gas, crude oil, etc. (Klein, 2011). Plastic is the most used synthetic material due to its low cost, lightweight, and extended durability. Global plastic production and use have dramatically increased since the 1960s, and it has been estimated to reach approximately 367 million tons in 2020 (Plastics Europe, 2021).

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The larger plastics break down into mesoplastics (5–25 mm) and microplastics (< 5 mm) over time (Andrady, 2011; MSFD Technical Subgroup on Marine Litter, 2013; OSPAR Commission, 2014). Microplastics are derived from the degradation of bigger plastic items (secondary microplastics), or they are directly discharged from the source, such as resin pellets, cosmetic scrubbers, or blasting abrasives (primary microplastics) (Andrady, 2011; Cole et al., 2011; Gregory, 1996; Mato et al., 2001). Moreover, the bulk of microplastics is fragmented particles from various sources (Gregory & Andrady, 2003), making effective management challenging.

Microplastics can enter the coastal–marine ecosystem in a variety of ways. Degradation of larger plastic items is the most prevalent method. Macroplastics (> 25 mm) can degrade through various processes, including oxidation, wave action, UV radiation, chemical deterioration, tire abrasion, and physical weathering (Andrady, 2011; Thompson et al., 2009). It results from improper waste management, such as using big plastic bags and fishing gear/nets (Boucher & Friot, 2017). As a result of the high surface area of microplastics and the hydrophobicity of the chemicals, they can absorb pollutants and act as vectors for a range of persistent pollutants, facilitating their mobility in aquatic environments (Cole et al., 2011; Yu et al., 2020).

Exceedingly small-sized plastics to potentially entangle a variety of terrestrial and marine animals, resulting in death (Gregory, 2009; Nunes et al., 2018; Ryan, 2018; Votier et al., 2011). The same chemicals that comprise plastic items have been detected in fish tissues, implying that trophic transfer of microplastics into the ecosystem might occur, which is very threatening and scary (Lu et al., 2016). The predator–prey interaction within the marine biota is the leading cause of the transmission of toxic chemicals (Andrady, 2011). In addition to containing potentially harmful microalgae like *Pseudo-nitzschia*, the plastisphere (all the plastic that builds up in marine ecosystems serves as a habitat for diverse types of microorganisms) can also accumulate potentially toxic elements such as lead (Pb) and copper (Cu), which can harm vulnerable species (Tarchi et al., 2022).

Information on the spatial–temporal distribution and abundance of microplastics is indispensable for developing management policies. Microplastics have been detected in coastal-marine waters worldwide (Chae et al., 2015; Cohen et al., 2019; Eriksen et al., 2018; Gray et al., 2018; Nakano et al., 2021; Sagawa et al., 2018; Sutton et al., 2016). Several reports have already been published regarding the concentration and distribution of plastic debris along with microplastics in the beach sediments (de Carvalho & Neto, 2016; Hidalgo-Ruz & Thiel, 2013; Ivar do Sul et al., 2009; Naji et al., 2019; Wessel et al., 2016). However, a few reports have investigated the concentrations of plastic debris with size classes in beach sediments (Jayasiri et al., 2013; Karthik et al., 2018; Lee et al., 2013; Martins & Sobral, 2011). Microplastics have also been analyzed in commercial salt or table salt instigated from well salt, lake salt, sea salt, or rock salt from different parts of the world (Gündoğdu, 2018; Iñiguez et al., 2017; Karami et al., 2017; Yang et al., 2015).

The Bay of Bengal has already been recognized as a hotspot of microplastic pollution (Eriksen et al., 2018; Hossain et al., 2020). A few reports have been published in Bangladesh on microplastics in fish (Ghosh et al., 2021; Hasan et al., 2022; Hossain et al., 2019; Siddique et al., 2022), shrimp (Hossain et al., 2020), beach sediments (Hossain et al., 2021; Rahman et al., 2020), and sea salt (Parvin et al., 2022). But, the exact mechanisms by which plastic debris with different size classes disperses throughout the environment are still poorly documented. Therefore, the current study investigates the distribution of microplastic and mesoplastic debris size classes in surface water, beach sediments, and crude salt along the Cox's Bazar coast of the northern Bay of Bengal, surrounded by vast sources of discarded plastic. This study also investigates significant correlations between mesoplastic and microplastic debris size classes in three different mediums: surface water, beach sediments, and crude salt.

2 Materials and methods

2.1 Study location

Cox's Bazar is a seaside city situated in the southeast part of Bangladesh in Asia. It features the northern Bay of Bengal's longest natural sandy beach (about 125 km), threatened by a growing fear known as plastic pollution. Samples were collected from different locations at different time points in the Cox's Bazar coast of the northern Bay of Bengal to know the spatial–temporal distribution of plastics in surface water, sandy beaches, and crude salt (Fig. 1).

2.2 Investigation of plastic debris in surface water

Surface water samples (n = 18) were collected from three stations, S1—near Moheshkhali Island (21° 30′ 45″ N and 91° 59′ 14″ E), S2—between Moheshkhali and Sonadia Island (21° 28′ 59″ N and 91° 57′ 36″ E), and S3—near Sonadia Island (21° 27′ 45″ N and 91° 54′ 25″ E) of Moheshkhali Channel with three replicates in March 2019, and January 2020 (Fig. 1). Sampling of plastics from water samples was performed according to Kovač Viršek et al. (2016). A manta net (mesh size: 300 μm; width of the opening: 60 cm) was used to collect microplastic and mesoplastic samples from the water surface. The net was deployed from the vessel's side, around 3–4 m from the vessel. For about 15 min, the action was set to proceed in a straight direction at a speed of

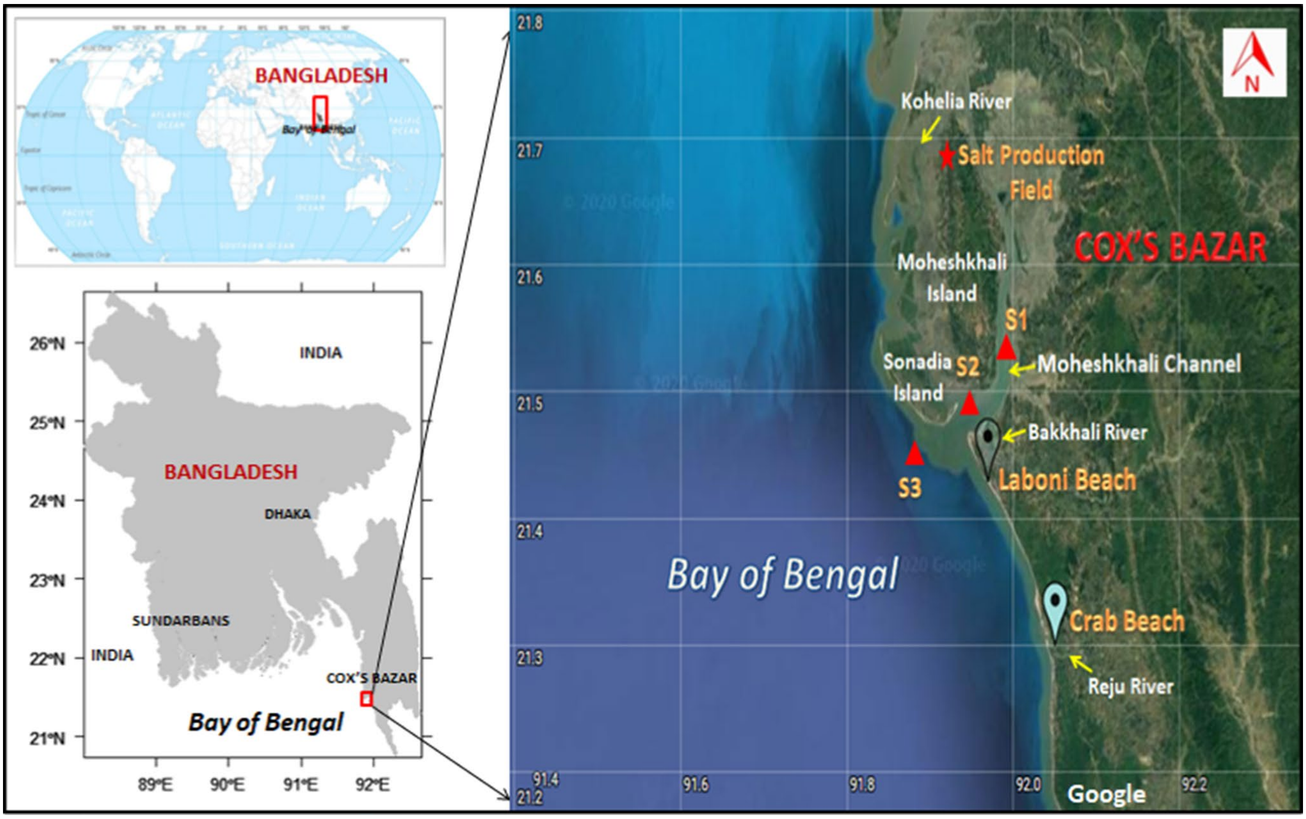

Fig. 1 Location of sampling sites in surface water at Moheshkhali Channel (S1—near Moheshkhali Island, S2—between Moheshkhali and Sonadia Island, and S3—near Sonadia Island); sandy beaches (Laboni Beach and Crab Beach), and salt production field at Moheshkhali Island, Cox's Bazar coast, Bangladesh (Source: Google)

approximately 2 knots. Then, the vessel was stopped, and the manta net was pulled from the water. The net was carefully rinsed from the outer side with clean water from the boat's water reservoir. The cod-end was removed safely, and the sample inside was sieved using a 300 µm mesh-sized sieve. The sieve was rinsed using 70% ethanol in a labeled glass jar with a glass funnel. The use of 70% ethanol is essential to preserve the sample. In addition, in visualizing the sample, ethanol helps to discolor the organisms; therefore, colorful plastic items become easier to find (Kovač Viršek et al., 2016). Then, the samples were processed in the Interdisciplinary Institute for Food Security (IIFS) laboratory at Bangladesh Agricultural University (BAU). Samples were poured through the metal sieves (successively using 5 mm, and 0.3 mm sieves), and all the litter objects (natural and artificial) were air-dried in a closed dish. All mesoplastic items were identified according to color (blue, green, yellow, etc.), type, and size and measured with a Digital Caliper (0.1 mm/0.01″ Resolution) along the longest axis and stored in separate clean glass vials.

Microplastic particles were separated from water samples according to Masura et al. (2015) with slight modification. Briefly, sieved samples (< 5 mm sized) were taken in 1 L glass beakers and dried in an oven (Genlab OV/200/F/DI, England) at 90 °C for 24 h. In each beaker, 20 mL of 0.05 M iron sulfate solution and 20 mL of 30% hydrogen peroxide were added, and the mixtures were kept at room temperature for 5 min. The mixtures were heated at 75 °C on a hotplate (AM4, Velp Scientifica, Italy) until gas bubbles were observed. If natural organic matter is noticeable, an additional 20 mL of 30% hydrogen peroxide was added. Approximately, 6 g salt (NaCl) was added per 20 mL of sample to raise the density of the solution (~ 5 M) and heated at 75 °C until the salt dissolved. The density separator was filled with the Wet Peroxide Oxidation solution (WPO), then covered loosely with aluminum foil. The WPO solution was poured into the density separator and covered loosely with aluminum foil. Solids settled in the separator were excluded, and floating solids were taken in a custom sieve (0.3 mm). The density separator was rinsed multiple times with distilled water to transfer all particles to the sieve.

Microplastics were identified under a microscope (Olympus CX41, Japan) at 4× to 100× magnification. Then, the main results of microplastic/mesoplastic samples were calculated as the number of microplastic/mesoplastic particles per sample (Kovač Viršek et al., 2016). These data were further normalized as per m^2 and km^2. The formula for normalization is microplastic/mesoplastic particles per sample divided by the sampling area. The sampling area is determined by multiplying the sampling distance (1 km) by the width of the manta net opening (60 cm).

2.3 Investigation of plastic debris in beach sediments

Beach sediment samples (n = 60) were collected from two beaches, Laboni beach, LB (21° 26′ 05″ N and 91° 57′ 51″ E), and Crab beach, CB (21° 19′ 47″ N and 92° 01′ 45″ E) with ten replicates/quadrats in March 2019, September 2019, and January 2020 (Fig. 1) during the lowest low tide. Two 100 m large transacts along the strandline/tideline were taken at each beach, and the distance between the two large transacts was approximately 0.5 km. Within every 100 m transact, five small quadrats (50 cm × 50 cm) were randomly selected for plastic debris sampling (Fig. 2). Within a 5 cm depth in the quadrat, all the debris (natural and manufactured) was sieved successively using 5 mm, and 0.3 mm metal sieves (Calcutt et al., 2018; Lee et al., 2013; MSFD Technical Subgroup on Marine Litter, 2013). Sediment samples were placed into the 5 mm sieve using a trowel and washed through the sieve using filtered seawater. All items larger than 5 mm remained in the top sieve. Items < 5 mm were passed through the 5 mm sieve but stayed on the top of the 0.3 mm sieve. The items (> 0.3 mm) were transferred using a metal spoon from the sieves into a labeled glass jar for storage and transport. Then, a minimum amount of 70% ethanol was added to each sample jar to preserve the sample. Next, the samples were processed in the laboratory of IIFS, BAU. The separation of the plastic debris from the other items of beach sediment samples was performed according to Calcutt et al. (2018). The sediment samples were sieved and air-dried in a closed dish. Plastic items with a size of > 5 mm were easily identified, and the size of each plastic item was measured with a Digital Caliper along the longest axis. The contents were carefully transferred into a glass serving dish containing a premade filtered salt water solution (35 g/L) to extract the microplastics (< 5 mm) from the samples. Most microplastics floated as they were lighter in density than the salt solution. Then, floating plastic particles were separated by visual identification and using a magnifying glass. Afterward, potential microplastics were identified under a microscope (Olympus CX41, Japan) at 4× to 100× magnification.

2.4 Investigation of plastic debris in crude salt

Three different crude salt (n = 27) samples (1 kg) with three replicates were collected from three separate salt beds (SB) at salt production sites (21° 42′ 01″ N and 91° 54′ 56″ E to 21° 42′ 03″ N and 91° 54′ 58″ E) of Moheshkhali Island, Cox's Bazar in March 2019, September 2019, and January 2020 (Fig. 1). Microplastics extraction from crude salt samples was accomplished according to Karami et al. (2017) and Yang et al. (2015) with slight modification. In brief, 200 g of

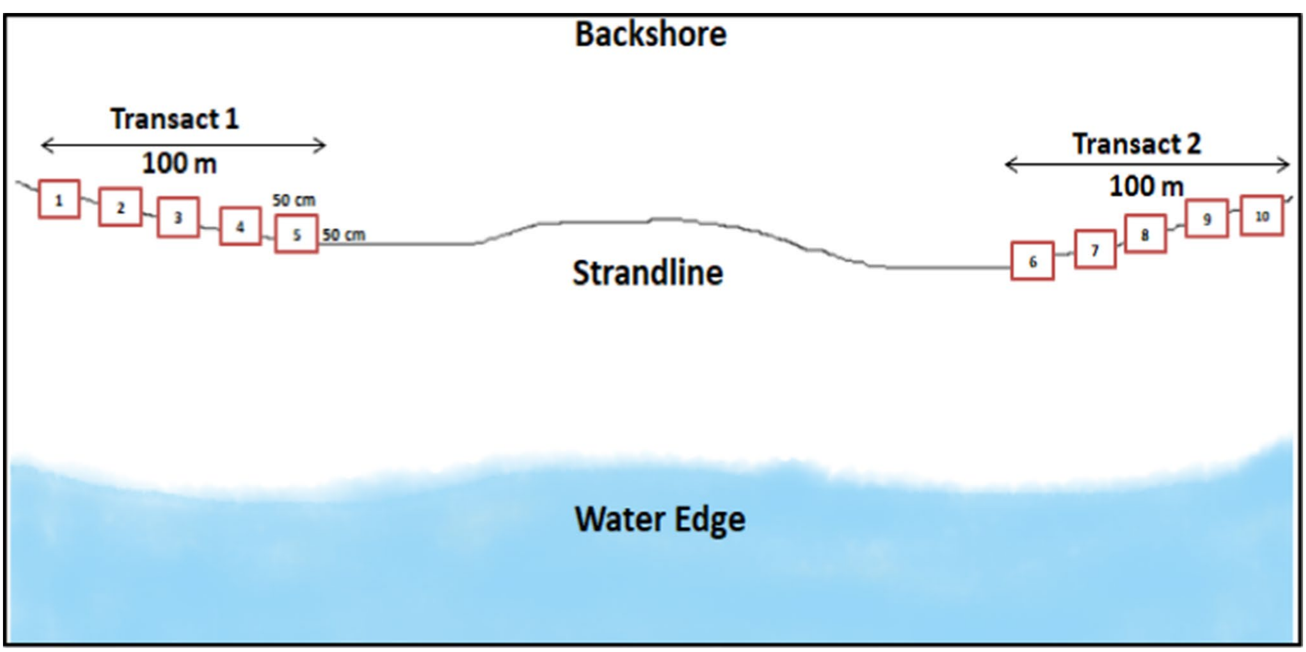

Fig. 2 Outline of beach plastic debris sampling at each beach. Five quadrats (50 cm × 50 cm) were randomly selected within each large 100 m transact to determine mesoplastic and microplastic abundances

crude salt was measured per replicate sample and transferred to a 2 L glass bottle. 200 mL of 30% hydrogen peroxide (H_2O_2) was added to each bottle to digest the organic matter. Then the bottles were covered with aluminum foil paper and placed in a shaking Water Bath (WiseBath, Witeg, Germany) at 65 °C with 80 rpm for 24 h. After 24 h, the bottles were kept at room temperature for 48 h. Next, after adding 800 mL of deionized water to each bottle, the bottles were stirred with a glass rod until the salt was dissolved and left at room temperature for 24 h.

The supernatants in the bottles were then filtered using a vacuum system with cellulose nitrate membrane filters (diameter: 47 mm, pore size: 5 µm), kept in sterile Petri dishes, and dried out at room temperature. The membrane filter was placed in a 100 mL glass bottle and treated with 10–15 mL of 4.4 M NaI. The bottles were sonicated using Ultrasonic Cleaner (WUC-D22H, Witeg, Germany) at 50 Hz for 5 min and centrifuged (Z 32 HK, HERMLE Labortechnik, Germany) at 500×*g* for 1 min to ensure the separation of microplastics. The supernatants were filtered through cellulose nitrate membrane filters (diameter: 47 mm, pore size: 5 µm) using a vacuum system for microscopic examination (Olympus CX41, Japan) at 4× to 100× magnification. The residual material at the bottom of the bottles was also transferred to clean Petri dishes for microscopic investigation.

2.5 Categorization of plastic items

The plastic samples were examined underneath a microscope (Olympus CX41 with camera DP22, Japan) for identification and quantification. The items were photographed, measured, and classified based on their maximum length, type, and color (Lusher et al., 2013). Moreover, the morphotypes of plastic items were categorized into fragment, film, fiber/thread, foam, pellet, and microbead (Kovač Viršek et al., 2016; CLEAR, 2017; Karami et al., 2017; Calcutt et al., 2018). Plastic items were also characterized into various colors, including white, red, black, pink, blue, translucent, orange, and green (Bellas et al., 2016; Naji et al., 2019; Nakano et al., 2021). We also used a hot needle test to differentiate between plastic items and organic components as an alternative detection technique. Any other matters such as algae fragments, animal shells, or other parts found on the filters were ignored throughout the study.

A representative number of mesoplastics and microplastics (> 300 µm to 25 mm items) from each morphotype were randomly selected to identify the plastic polymer types and analyzed with a Fourier Transform Infrared Spectroscopy (FTIR) (FTIR-4600, JASCO Inc., Japan) equipped with an Attenuated Total Reflection (ATR) unit. The spectrum range used to identify each plastic was 4000 to 400 cm^{-1} with a spectral resolution of 4 cm^{-1}. Sixteen co-scans were done for each measurement, and a background measurement was done before measuring each particle. The JASCO Spectra Manager™ II software was used to collect data. Using the KnowItAll® Informatics System 2018, the obtained spectrum was compared to the polymer spectrum from commercial libraries (JASCO Edition, USA). Each particle was analyzed several times, with the results chosen based on the spectrum's accuracy compared to the reference library.

2.6 Quality control and assurance

Glass or metal items were used rather than plastic to avoid contamination. All sampling equipment was cleaned and kept in a storage box before use. All buckets and jars were covered with lids to prevent microplastic fibers from blowing into the containers. The sampling team used masks, gloves, and garments made of natural fibers rather than synthetic clothing. All liquids (deionized water, hydrogen peroxide, etc.) were filtered (5 µm) before use to avoid contamination in the laboratory. All the glassware, containers, filtration units, and other necessary instruments were also cleaned with filtered water. When samples were unused, they were instantly covered with aluminum foil paper.

Furthermore, to cross-check the airborne contamination, 500 mL of filtered distilled water in a 1 L glass beaker was kept at three places in the lab for one week during the sample processing and extraction method. The blank control samples were then filtered and observed under a microscope. Any particles identified were examined using FTIR. Finally, the value was subtracted from each sample to remove the error due to airborne contamination.

2.7 Statistical analysis

The number of microplastics and mesoplastics (mean ± SD; maximum and minimum values) was estimated using descriptive statistics. Two-way ANOVA was performed to understand plastic debris' temporal and spatial abundance in surface water, sandy beaches, and crude salt, followed by Tukey's HSD post hoc comparisons. Before the analyses, research data were further verified for homoscedasticity and normality assumptions using Levene's, and Shapiro–Wilk's tests, respectively. A general linear regression analysis was used to determine the relationship between the abundances of microplastic and mesoplastic size classes. The type and color of microplastics and mesoplastics were determined in frequency percentage (%). Statistical analyses were performed using the SPSS software (version 26, IBM, USA), and variations between the mean values at $p < 0.05$ were considered significant.

3 Results

3.1 Microplastics and mesoplastics in surface water

Mean concentrations of plastics in the surface water of Cox's Bazar coast during March 2019, and January 2020 were observed to be 0.022 and 0.021 items/m^2 for microplastics, while 0.005 and 0.004 items/m^2 for mesoplastics but they did not vary significantly ($p > 0.05$) (Table 1, Fig. 3a). Mean abundance of microplastics were recorded to be 0.023, 0.021 and 0.021 items/m^2 where mesoplastics were 0.006, 0.004 and 0.004 items/m^2 in S1, S2 and S3, respectively, throughout the study period ($p > 0.05$) (Table 1, Fig. 3b). Moreover, there were no significant variations ($p > 0.05$) in the abundance of plastics in months, stations, and their interaction except the abundance of microplastics in the months*stations ($p < 0.01$) (Table 1).

Six different types (fragment, fiber, film, foam, pellet, and microbead) of plastics were recorded in the surface water of the Moheshkhali Channel. In the case of temporal distribution, the dominant type of microplastics was fragments (37%) in surface water, found in March 2019 (Table 2). However, pellets (3%) and microbeads (2%) were recorded as the least amount in January 2020. Meso-fragments (50%) dominated in January 2020 (Table 2). In the case of spatial distribution, micro-fragments (43%) were prevalent in S1, while meso-fragments (54%) were dominant in S3 (Table 3). This study elucidated that among different colored plastics, white-colored microplastics (31%) and mesoplastics (37%) were dominant in March 2019 and January 2020, respectively (Table 4). In the case of spatial distribution, the highest white-colored microplastics (35%) and mesoplastics (53%) were recorded in S1 and S2, respectively (Table 5). There was a strong and positive correlation (r 0.843; $p < 0.001$) between mesoplastics and microplastics abundance in surface water (Fig. 4a). Therefore, microplastics were prevalent in locations with high mesoplastic concentrations. The linear regression equation was $y = 1.53x + 0.01$, and the coefficient of determination (R^2) value was 0.710 for the surface water of Moheshkhali Channel, Cox's Bazar.

3.2 Microplastics and mesoplastics in beach sediments

In the case of beach sediments, mean concentrations of plastics were recorded to be 69.40, 140.60, and 41.00 items/m^2 for microplastics and 20.00, 43.20, and 14.00 items/m^2 for mesoplastics during March 2019, September 2019, and January 2020, respectively with significant variations between months ($p < 0.001$) (Table 1, Fig. 3c). Mean concentrations of mesoplastics were recorded to be 22.53 and 28.93 items/m^2 in LB and CB, respectively ($p < 0.05$) where microplastics were 70.80 and 96.53 items/m^2 in LB and CB, respectively ($p < 0.001$) (Table 1, Fig. 3d). Moreover, significant variations in abundance of plastics were observed in months, beaches and their interaction except the abundance of mesoplastics in the months*beaches ($p > 0.05$) (Table 1).

In the case of temporal distribution, micro-fragments (33%) and micro-fibers (29%) were the prevalent types recorded in September 2019 (Table 2). Meso-fibers (38%) and meso-fragments (37%) were dominant in September 2019 and January 2020, respectively (Table 2). In the case of spatial distribution, micro-fragments (36%) and micro-fibers (31%) were dominant in LB (Table 3). However, micro-foams (20%) and meso-foams (24%) were dominant in CB. A high amount of meso-fibers (36%) and meso-fragments (33%) were observed in LB (Table 3). This study revealed that among different colored plastics, both white microplastics (32%) and white mesoplastics (23%) were dominant in January 2020 (Table 4). In the case of spatial distribution, white microplastics were also prevalent in both LB (32%) and CB (25%). However,

Table 1 Two-way ANOVA test results of analyzed data at different time points, locations, and interactions in surface water, beach sediment, and crude salt of the Cox's Bazar coast

Parameter	Source	Mesoplastics			Microplastics		
		df	F	**p* value	*df*	F	**p* value
Surface water (n = 18)	Months	1	0.970	0.344	1	0.903	0.361
	Stations	2	2.106	0.164	2	1.799	0.207
	Months*stations	2	0.742	0.497	2	6.948	**< 0.01**
Beach sediment (n = 60)	Months	2	53.651	**< 0.001**	2	143.205	**< 0.001**
	Beaches	1	6.930	**< 0.05**	1	27.015	**< 0.001**
	Months*beaches	2	0.144	0.866	2	3.911	**< 0.05**
Crude salt (n = 27)	Months	2	0.026	0.974	2	1.952	0.171
	Salt beds	2	0.974	0.397	2	0.122	0.886
	Months*salt beds	4	0.382	0.819	4	0.156	0.958

df degree of freedom.

**p* values in bold indicate significant differences

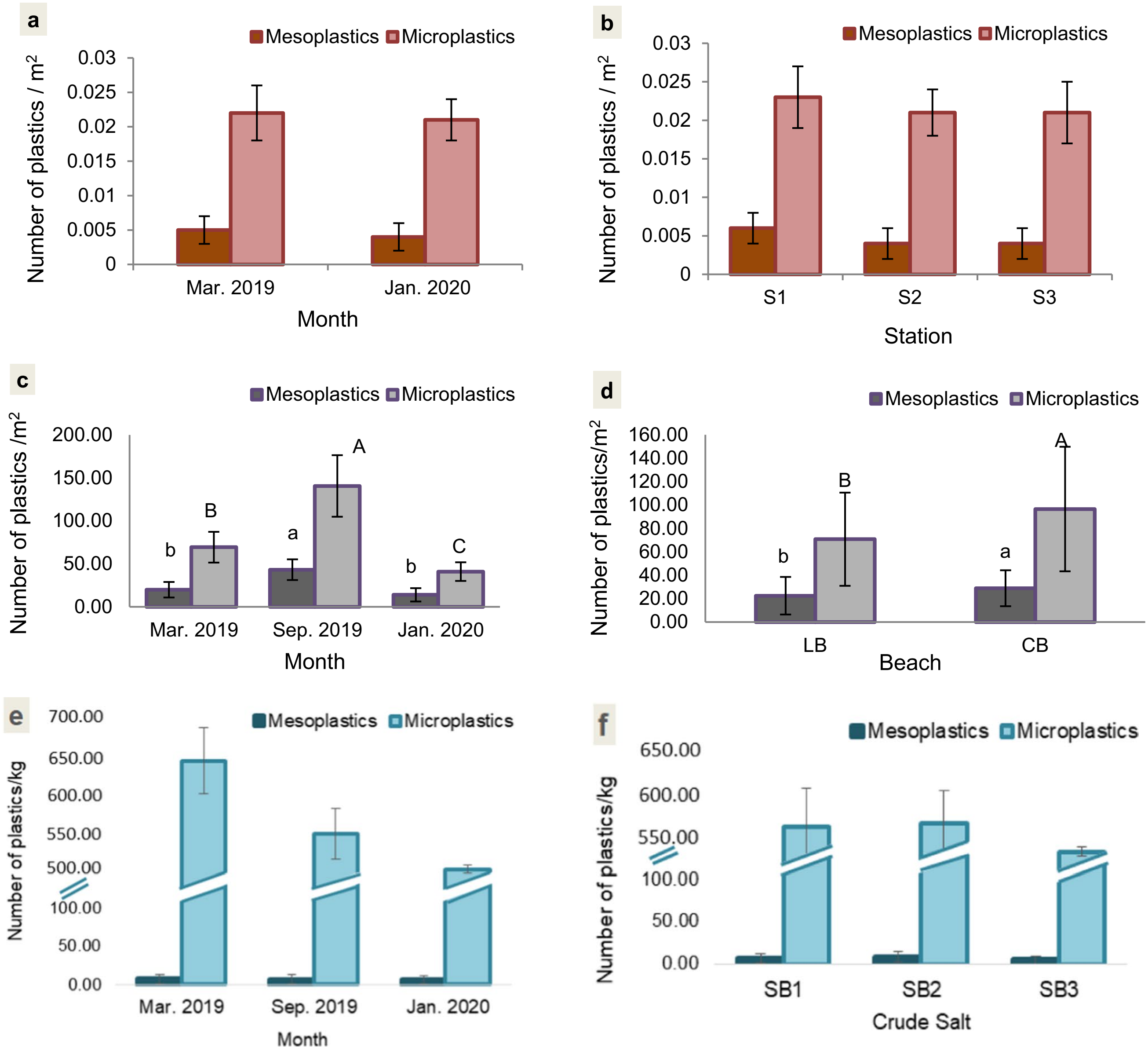

Fig. 3 Abundance of plastics in the Cox's Bazar coast: **a** temporal and **b** spatial distribution of plastics in the surface water ($p > 0.05$); **c** temporal and **d** spatial distribution of plastics in the beach sediment; values accompanied by different letters indicate statistically significant differences ($p < 0.05$); **e** temporal, and **f** spatial distribution of plastics in the crude salt ($p > 0.05$) [S1 = Station 1; S2 = Station 2; S3 = Station 3; LB = Laboni Beach; CB = Crab Beach; SB1 = Salt Bed 1; SB2 = Salt Bed 2 and SB3 = Salt Bed 3]

black color was common in CB (25%) for mesoplastics (Table 5). There was a strong and positive correlation (r 0.918; $p < 0.001$) between mesoplastics and microplastics abundance in beach sediments (Fig. 4b), which indicates microplastics were prevalent in locations with high mesoplastic concentrations. The linear regression equation was $y = 2.79x + 11.90$, and the coefficient of determination (R^2) value was found as 0.842 for Cox's Bazar beach sediments.

3.3 Microplastics and mesoplastics in crude salt

In salt beds, mean concentrations of plastics were recorded to be 630, 535, and 490 items/kg for microplastics, and 7, 6, and 6 items/kg for mesoplastics during March 2019, September 2019, and January 2020, respectively, with no significant variations between months ($p > 0.05$) (Table 1; Fig. 3e). In case of spatial distribution, mean concentrations of plastics were recorded to be 561, 565, and 532 items/m^2

Table 2 Temporal occurrence (%) of different type of microplastics and mesoplastics in surface water, beach sediment, and crude salt of the Cox's Bazar coast

Plastic	Type (%)	Surface water		Beach sediment			Crude salt		
		Mar. 2019	Jan. 2020	Mar. 2019	Sep. 2019	Jan. 2020	Mar. 2019	Sep. 2019	Jan. 2020
Micro	Fragments	37	34	30	33	32	24	25	25
	Films	25	22	21	23	19	19	18	16
	Fibers	26	28	26	29	26	33	35	42
	Foams	12	11	23	13	13	15	12	13
	Pellets	0	3	0	2	10	0	0	0
	Microbeads	0	2	0	0	0	9	10	4
Meso	Fragments	44	50	32	26	37	39	33	25
	Films	15	14	14	20	17	15	17	17
	Fibers	30	32	26	38	30	46	42	50
	Foams	11	4	28	16	16	0	8	8

Table 3 Spatial occurrence (%) of different type of microplastics and mesoplastics in surface water, beach sediment, and crude salt of the Cox's Bazar coast

Plastic	Type (%)	Surface water			Beach sediment		Crude salt		
		S1	S2	S3	LB	CB	SB1	SB2	SB3
Micro	Fragments	43	27	36	36	29	24	24	26
	Films	25	22	24	21	21	18	17	19
	Fibers	21	30	30	31	26	38	34	36
	Foams	11	17	8	10	20	12	16	11
	Pellets	0	3	0	2	4	0	0	0
	Microbeads	0	1	2	0	0	8	9	8
Meso	Fragments	38	53	54	33	27	33	31	45
	Films	24	7	8	17	18	17	13	22
	Fibers	33	33	23	36	31	50	56	22
	Foams	5	7	15	14	24	0	0	11

S1 Station 1, *S2* Station 2, *S3* Station 3, *LB* Laboni Beach, *CB* Crab Beach, *SB1* Salt Bed 1, *SB2* Salt Bed 2, *SB3* Salt Bed 3

for microplastics and 7, 9, and 5 items/m^2 for mesoplastics in SB1, SB2, and SB3, respectively but they did not vary significantly ($p > 0.05$) (Table 1, Fig. 3f). Moreover, there were no significant variations in abundance of plastics for months, salt beds and their interaction ($p > 0.05$) (Table 1).

In the case of temporal distribution, both micro-fibers (42%) and meso-fibers (50%) were dominant in January 2020 (Table 2). However, micro-fibers (38%) were dominant in SB1, while meso-fibers (56%) were dominant in SB2 (Table 3). Among different colored plastics, black microplastics (33%) were dominant in January 2020, while black mesoplastics (42%) were dominant in both September 2019 and January 2020 (Table 4). Black microplastics (30%) were dominant in both SB1 and SB2, while black mesoplastics (56%) were prevalent in SB2 (Table 5). The linear regression equation was $y = 15.97x + 444.65$, and the coefficient of determination (R^2) value was 0.350 for crude salt. Besides, a moderate and positive correlation (r: 0.592; $p < 0.001$) was observed between mesoplastics and microplastics abundance in crude salt samples at Moheshkhali Island, Cox's Bazar coast (Fig. 4c). The types of plastics detected in the Cox's Bazar coast have been shown in Fig. 5a–e.

3.4 Chemical categorization

In the present study, the identified polymer types from the northern Bay of Bengal, Bangladesh coast were polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyamide, polyvinylchloride, ethylene propylene diene monomer, and polyurethane. In surface water, the most common polymer was polyethylene (28%), followed by polypropylene (25%), polystyrene (17%), and polyethylene terephthalate (15%) (Fig. 6a). Polyethylene (29%) was also the prominent polymer in beach sediments, followed by polypropylene (27%), polystyrene (13%), and polyethylene terephthalate (12%) (Fig. 6b). In crude salt, polyethylene (31%), polypropylene (28%), polystyrene (18%), and polyethylene terephthalate (14%) were also reported (Fig. 6c).

Table 4 Temporal occurrence (%) of different color of microplastics and mesoplastics in surface water, beach sediment, and crude salt of the Cox's Bazar coast

Plastic	Color (%)	Surface water		Beach sediment			Crude salt		
		Mar. 2019	Jan. 2020	Mar. 2019	Sep. 2019	Jan. 2020	Mar. 2019	Sep. 2019	Jan. 2020
Micro	Red	11	7	10	11	8	16	14	13
	White	31	29	29	27	32	11	15	17
	Blue	13	20	16	19	19	20	23	27
	Black	22	18	23	23	19	26	31	33
	Pink	0	3	5	2	4	7	8	7
	Translucent	13	12	8	14	11	6	4	0
	Orange	0	0	4	3	2	0	0	0
	Green	10	11	5	1	5	14	5	3
Meso	Red	7	9	13	12	4	8	0	8
	White	33	37	9	22	23	8	17	17
	Blue	26	14	26	24	21	23	8	8
	Black	22	23	34	18	33	38	42	42
	Pink	0	5	7	10	0	0	0	0
	Translucent	8	9	11	9	16	23	33	25
	Green	4	3	0	5	3	0	0	0

Table 5 Spatial occurrence (%) of different color of microplastics and mesoplastics in surface water, beach sediment, and crude salt of the Cox's Bazar coast

Plastic	Color (%)	Surface water			Beach sediment		Crude salt		
		S1	S2	S3	LB	CB	SB1	SB2	SB3
Micro	Red	8	9	9	9	11	16	15	13
	White	35	31	24	32	25	15	14	14
	Blue	13	16	20	17	18	23	21	24
	Black	21	18	21	24	23	30	30	29
	Pink	0	3	1	3	4	5	9	8
	Translucent	11	13	15	11	11	3	2	5
	Orange	0	0	0	1	5	0	0	0
	Green	12	10	10	3	3	8	9	7
Meso	Red	9	0	15	10	12	16	0	0
	White	29	53	23	20	18	0	19	23
	Blue	10	27	31	24	24	17	6	22
	Black	24	20	23	24	25	25	56	33
	Pink	5	0	0	7	8	0	0	0
	Translucent	14	0	8	11	10	42	19	22
	Green	9	0	0	4	3	0	0	0

S1 Station 1, *S2* Station 2, *S3* Station 3, *LB* Laboni Beach, *CB* Crab Beach, *SB1* Salt Bed 1, *SB2* Salt Bed 2, *SB3* Salt Bed 3

Spectral characteristics of the representative polymers have been presented in Fig. 6d.

4 Discussion

In the present study, microplastics recorded from the surface water of Cox's Bazar coast along the northern Bay of Bengal were 0.017–0.028 items/m^2 (17,000–28,000 items/km^2), which is almost similar to Eriksen et al. (2018) estimation. According to Eriksen et al. (2018), the abundance of microplastics in the Bay of Bengal ranged from a few hundred to 20,000 items/km^2; however, in one region, the quantity exceeded 100,000 microplastics/km^2. Moreover, microplastic abundances fluctuated around 10,000 items/km^2 in the South Pacific but surpassed > 50,000 items/km^2 near the islands of Rapa Nui and Salas and Gomez (Eriksen et al., 2018). However, microplastic abundances in Incheon/

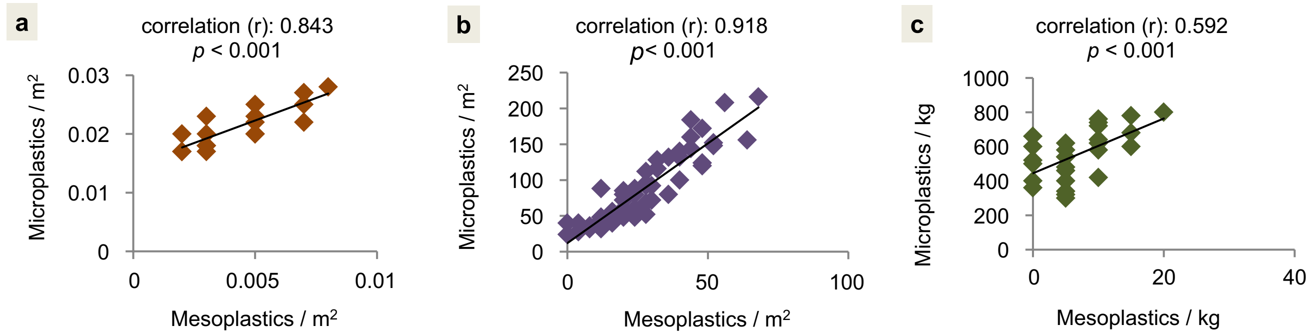

Fig. 4 Linear regressions of plastic abundances between the mesoplastic and the microplastic size classes from **a** surface water, **b** beach sediment, and **c** crude salt of Cox's Bazar coast

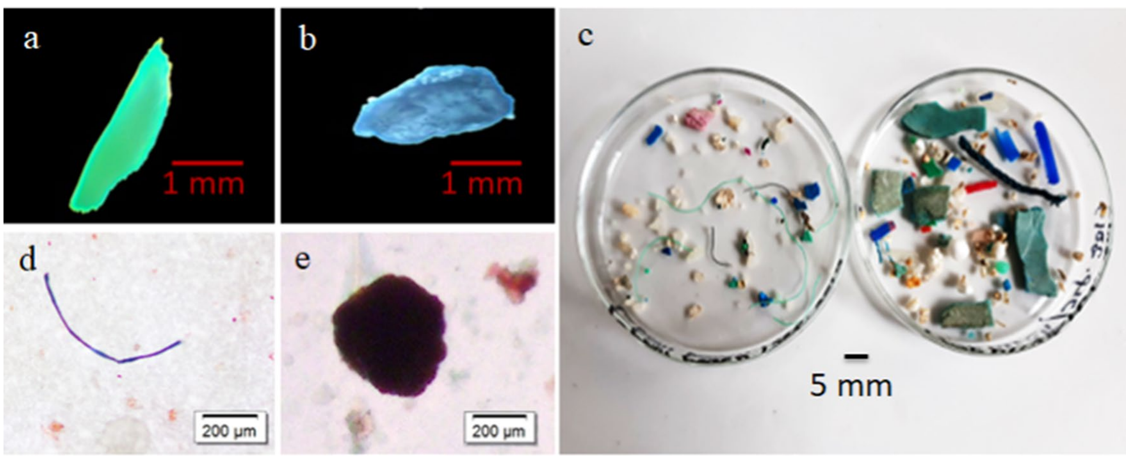

Fig. 5 Examples of some plastic items observed in surface water (**a** fragment, **b** foam), beach sediment (**c** fragments, foams, fibers, films, pellets, etc.), and crude salt (**d** fiber, **e** microbead) of Cox's Bazar coast

Kyeonggi coastal region, Korea; Delaware Bay, USA; Hiroshima Bay, Japan; San Francisco Bay, USA; and Tokyo Bay, Japan was found to be higher than the present findings as documented by Chae et al. (2015), Cohen et al. (2019), Sagawa et al. (2018), Sutton et al. (2016), and Nakano et al. (2021), respectively. The abundance of microplastics in the surface water of the northern Bay of Bengal, Bangladesh, was lower than that reported in other bays due to its geographical features (Nakano et al., 2021). In this study, the abundance of plastics in surface water was higher in March 2019 (early summer) than in January 2020 (winter). In contrast, in the case of spatial distribution, the abundance of plastics was higher at S1 (near Moheshkhali Island). According to our investigations, currents, river and neighboring channel flows, fishing activities, local transportation activity, and tourism may all have a role in the variation in the spatial–temporal distribution along the studied region.

In the current study, microplastics recorded from beach sediments in Cox's Bazar were 24–216 items/m^2 (or 24×10^6 to 216×10^6 items/km^2). However, Hossain et al. (2021) recorded 200–378.8 items/kg microplastic concentrations from the Cox's Bazar beach sediments. Koongolla et al. (2018) recorded 0–157 items/m^2 in the beach sand in Southern Sri Lanka, which is more or less similar to our findings. However, the higher abundance of microplastic concentrations in the South Korean beaches (Lee et al., 2013), Guanabara Bay of Brazil (de Carvalho & Neto, 2016), and Charleston Harbor and Winyah Bay of USA (Gray et al., 2018) were found than that of the findings of our present study. In addition, Wessel et al. (2016) reported 50.6 microplastics/m^2 in marine-influenced regions and 13.2 microplastics/m^2 in freshwater-dominated regions. Plastic material on beaches is subjected to UV radiation, which, combined with the physical impacts of currents, tides, waves, and wind, causes mechanical or chemical weathering and, finally, embrittlement (Cooper & Corcoran, 2010; Corcoran et al., 2009).

CB is found to be much more polluted with plastic debris than LB. CB is created through siltation by the Reju River. Therefore, high plastic pollution might have been due to transporting of plastic particles by the river and sea. Earlier

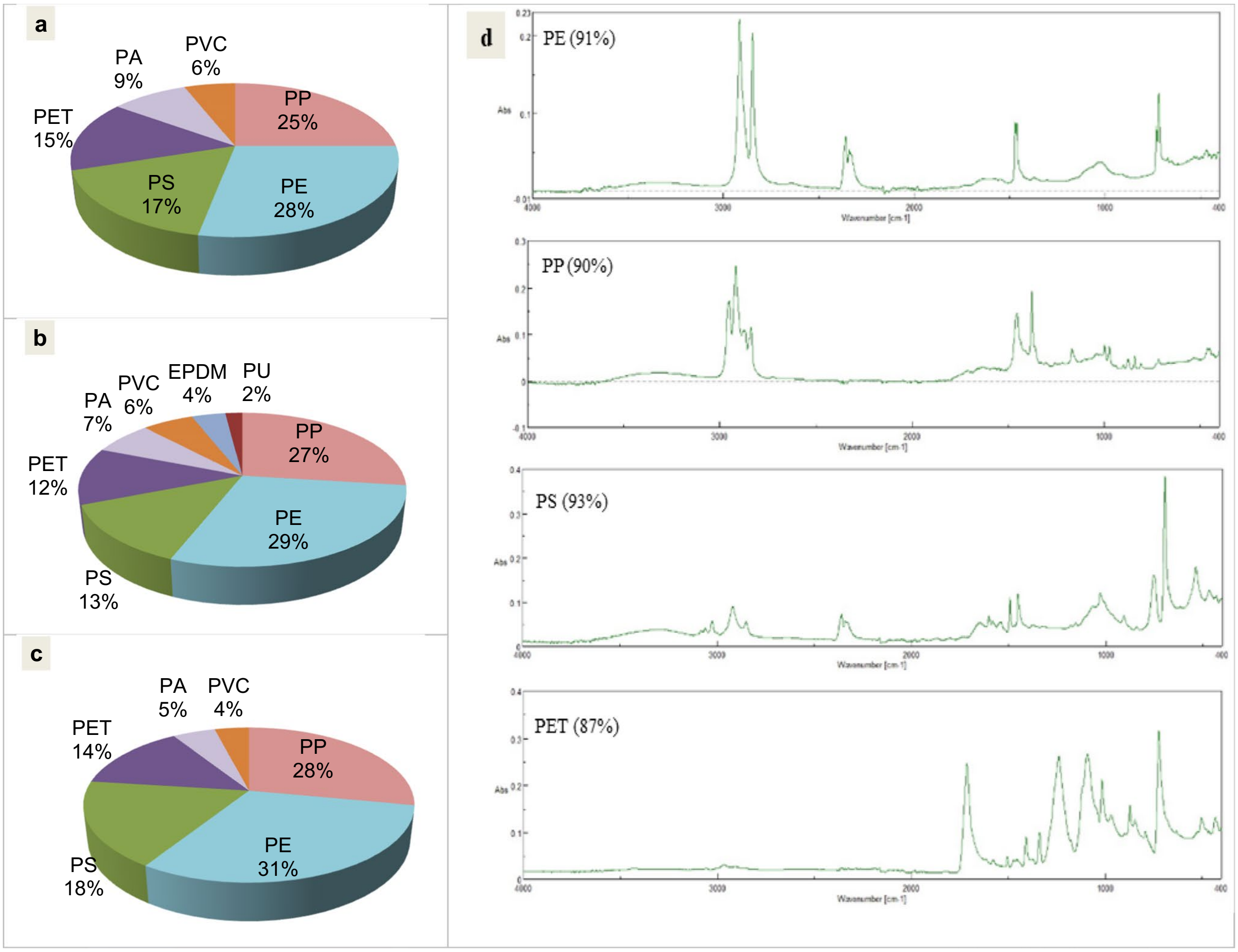

Fig. 6 Plastic polymer types distribution: **a** surface water, **b** beach sediment, **c** crude salt, and **d** Fourier Transform Infrared (FTIR) spectra of representative microplastic polymers (PE, PP, PS, and PET); the value in the brackets indicates the matches of the spectra with the reference spectra [PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; PA = polyamide; PVC = polyvinylchloride; EPDM = ethylene propylene diene monomer; and PU = polyurethane]

studies also showed that riverine inputs are significant sources of marine plastic waste (Rech et al., 2014; Zhao et al., 2015). Our analysis also indicates that the higher quantity of plastic debris in beach sediments in September 2019 might have been due to the effect of late monsoon rainfall in Bangladesh. Furthermore, variations in the spatial–temporal distribution of the beach sediments may be attributed to many factors, including beach direction, tidal currents, wave energy, riverine discharges, tourist activities, beachside restaurants, and hotels (Browne et al., 2011; Hossain et al., 2021). In addition, other contributing factors to the enormous quantity of plastic items in beach sediments, including recreational activities and collecting bivalve shells for manufacturing ornaments by the local people of Cox's Bazar, which implies that land-based sources (Jayasiri et al., 2013) be responsible for considerable inputs to plastic pollution in the study area.

In the present study, we found the number of microplastics as 300–800 items/kg with a mean value of 554 items/kg in crude salt. In Bangladesh, salt industries collect crude salt from sea salt beds, which exists in these industries. From this study, we can assume that the occurrence of plastic debris at salt beds of Moheshkhali Island, Cox's Bazar, in different months might have been due to some factors such as tidal influence, rainfall, discharges of the river (e.g., Kohelia River), and preparation of salt beds. The World Health Organization recommends a healthy adult intake of 5 g of salt per day (WHO, 2012), whereas the average daily intake is 10 g globally (Mozaffarian et al., 2014). Gündoğdu (2018) reported that people consume 248.5–302.4 items of microplastics per year when they consume sea salt. This number was reported as 1000 items per year in China (Yang et al., 2015) and 37 per year globally (Karami et al., 2017). However, the amount of salt consumed in Bangladesh is very high. People can be exposed to microplastics by consuming salt at a rate of 13,088 items per year in Bangladesh, which is worrisome and could pose a high risk to public health (Parvin et al., 2022). As all these figures are proportional to the amount of salt consumed, it stands to reason that if salt intake is lowered and factory filtration is improved to remove microplastics, these figures will fall (Gündoğdu, 2018).

In this study, fragments and fibers were the most common types of particles compared to other types, consistent with prior investigations. Fragments (75%) were identified as dominant throughout the study in the surface water of Tokyo Bay (Nakano et al., 2021). However, Hossain et al. (2021) reported that fibers were the most common microplastics identified on sandy beaches of Cox's Bazar, accounting for 53% of total microplastics. Sediments from the Belgian coast (Claessens et al., 2011), Changjian estuary (Peng et al., 2017), Lake Erie (Dean et al., 2018), and Tamil Nadu (Sathish et al., 2019) all have high quantities of fibers, with values of 59.8%, 93%, 63%, and 70.5%, respectively. Nevertheless, fragments (47–50%) were the most common type identified from beach sediments by Karthik et al. (2018). Furthermore, fragments were also dominant in the bottom sediments of the Lagoon of Venice (87%) and Tokyo Bay (75%), as stated by Vianello et al. (2013) and Matsuguma et al. (2017), respectively. Among different types of plastic debris, styrofoams were found to be most dominant in beach sediments by Lee et al. (2013) and Heo et al. (2013). According to Parvin et al. (2022), fibers and fragments were most common in commercial sea salt in Bangladesh. In addition, Yang et al. (2015) identified fragments and fibers as the dominant type of sea salt from China, while fibers (> 70%) were reported as dominant in table salt in Turkey (Gündoğdu, 2018) and fragments (63.8%) were identified as prevalent in table salt from various countries (Karami et al., 2017). Fibers may be transported to beach sediments and salt beds via sewage, surface runoff, and river discharges from fishing lines, nets, gears, textiles, and washing machine discharges (Browne et al., 2011; Hernandez et al., 2017; Murphy et al., 2016). According to Nakano et al. (2021), artificial grass and fishing gear were the sources of green-colored fragments and lines in Tokyo Bay, respectively.

Color is a critical characteristic that affects the intake of microplastics by marine biota. Predators may be attracted to specific colors when they resemble the color of their prey/food (Abayomi et al., 2017; Kühn et al., 2015). In the present study, white and black particles were the colors to show considerable spatial–temporal variations in coastal-marine water and sandy beaches. In contrast, black and blue were common in the crude salt of Moheshkhali Island, Cox's Bazar. Hossain et al. (2021) recorded purple (18%) and pink (14%) as common colors, while Peng et al. (2017) found 42% transparent and 58% colored particles in beach sediments, which are analogous to the current study. However, Hossain et al. (2019) reported white/transparent (26–68%) as the prevalent color of microplastics, followed by black (20–34%) in marine fish in Bangladesh, which supports the present findings. The most common color of microplastics retrieved across all sampling stations was black, accounting for almost 41% of the particles collected from the sediments (Naji et al., 2019). The color variation could be attributable to the fact that they came from different sources (Sathish et al., 2019). According to Peng et al. (2017), laundry garments are the leading source of multicolored microplastics entering aquatic habitats. In addition, Hossain et al. (2021) suggested that colorful microplastics may originate from synthetic and organic constituents, which would necessitate more extensive research.

The regression analysis in this study reveals that microplastics were frequent in locations with high mesoplastic concentrations, which coincides with the findings of Lee et al. (2013) and Karthik et al. (2018). Hence, according to our findings, the northern Bay of Bengal is detected as a hotspot of plastic debris with different size classes. As we noticed, numerous plastic items from surface water and beach sediments of Cox's Bazar coast, different fish, crustaceans (e.g., crab), bivalves (e.g., oyster, mussel), etc., may be affected by plastic pollution. Besides, various plastic items recorded in the crude salt of Cox's Bazar coast indicate the possibility of ingesting such particles through food consumption.

Among the identified type of polymers (e.g., polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and polyamide), polyethylene was the most frequently found polymer in surface water, sandy beaches, and crude salt of Cox's Bazar coast that agree with other reported studies (Gündoğdu, 2018; Karthik et al., 2018; Koongolla et al., 2018; Nakano et al., 2021). The single-use of food packaging or polyethylene bags, as well as improper debris management at the Bay of Bengal basin, might be the potential reason for the film plastics as polyethylene polymer. Polypropylene was the second prominent polymer in the current study, extensively used in packaging, car bumpers, folders, and so on (Plastics Europe, 2015). Furthermore, polypropylene (0.90–0.91 g/cm^3) and polyethylene (0.91–0.96 g/cm^3) have a low density, which allows them to float on the water surface and be easily directed into the salt beds, Cox's Bazar, according to our investigations. Their low density may also help them spread while airborne (Karami et al., 2017).

In this study, the fragments of food packaging, bottles, containers, toys, pipe, as well as pieces of styrofoam sheets/coverings, and other plastic items, are thought to have come from weathering or breakdown of larger plastic items dumped by the local people/tourist near the Bay of Bengal. Polyethylene terephthalate is the most widely used polyester in the textile industry; therefore, it can also be found in the oceans and the global environment as fibers (Iñiguez et al., 2017). Moreover, we also identified polyamide in surface water, sediments, and crude salt samples, which might come from dumping damaged or useless fishing gears, nets, ropes, floats, baskets, or bags near Cox's Bazar coast.

5 Conclusions

The present study reports the quantitative evaluation of plastic debris in coastal-marine water, sandy beaches, and crude salt in Cox's Bazar along the northern Bay of Bengal, Bangladesh. In this study, the mean concentrations of microplastics (< 5 mm) in surface water, beach sediments, and crude salt were found to be 0.021–0.023 items/m^2, 41.00–140.60 items/m^2, and 490–630 items/kg, respectively. However, the mean concentrations of mesoplastics (5–25 mm) in surface water, beach sediments, and crude salt were found to be 0.004–0.006 items/m^2, 14.00–43.20 items/m^2, and 5–9 items/kg, respectively. The most common polymers in Cox's Bazar Coast were polyethylene, polypropylene, polystyrene, and polyethylene terephthalate. The high concentration of microplastics in river-inclined sandy beaches suggests that a considerable quantity of the particles is land-based. In addition, the lack of effective management techniques and recycling facilities is the main reason for this plastic pollution. Even though beach cleanup activities are conducted to preserve the scenic value of beaches, tiny plastic particles are rarely eliminated. Consequently, there might have been a significant danger to marine biota due to possible ingestion. In addition, numerous microplastics have been found in the crude salt of Cox's Bazar coast, suggesting the possibility of ingesting such particles through food. If we could raise public awareness about the dangers of plastic pollution, we could make a significant difference in reducing pollution from plastic sources. In the promising future, extensive research must be done to improve plastic contamination controls, environmental conservation, and management of this coastal region.

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Author contributions KF: sample collection and analyses, formal analysis, writing—original draft preparation. KAS: resources, writing—review and editing. SMM: sample collection and analyses. MJA: formal analysis, writing—review and editing. SJH: resources. MHU: sample collection. HA: resources, supervision, writing—review and editing. HR: conceptualization, supervision, writing—review and editing. All the authors approved the final version of the manuscript.

Data availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent to participate All names in the author list have been involved throughout the study and writing.

Consent for publication This manuscript was approved by all the authors. Moreover, this work has original research that has not been published previously and is not under consideration for publication elsewhere, in whole or in part.

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