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Review

Characterization, Risk, and Pathway of Microplastics in Coastal Areas of the Bay of Bengal: A Systematic Review and Quantitative Synthesis

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Abstract: Microplastics (MPs) have become a global concern, as they are widespread in aquatic environments and pose ecological risk, which threatens both marine and freshwater organisms. This study seeks to provide a comparative and comprehensive illustration of MP pollution in the water and sediments of the Bay of Bengal coastal areas, including islands, estuaries, and beaches. It also highlights associated risks and pathways of microplastics. The analysis is based on data reported in peer-reviewed publications from the past decade. The study found microplastics in water varied widely, from 2.35 to 263,000 MPs/m^3, while sediments ranged between 1 and 815 MPs/kg. The highest levels were observed at the Thoothukudi coast in water samples and the Muttukadu backwater estuary in sediments. Transparent and white colored particles were reported as dominant in 53% and 65% studies on water and sediment, respectively, which were largely linked to packaging items, plastic bags, and other disposable materials. Microplastics sizes <1 mm were the most prevalent in the study area, which may result from the extensive degradation of plastic debris. Fibers and fragments were the dominant shapes in both water and sediment that may come from synthetic textiles, fishing gear, packaging materials, etc. Polyethylene was the most frequently reported polymer, with packaging materials and single-use plastics being possible sources, followed by polypropylene, polyamide, polystyrene, and PET. Statistical analyses, including Pearson's correlation, PCA, and HCA, showed correlations among shapes, colors, sizes, and polymers, reflecting multiple pollution sources. Risk assessments through PLI, PHI, and ERI indices revealed that most sites exceeded extreme pollution thresholds, highlighting serious ecological threats to biodiversity and human health. Therefore, integrated regional strategies are urgently needed to mitigate this issue.

Keywords: microplastics; abundance; risk assessment; pathway; Bay of Bengal

Highlights

- Microplastic abundance in the Bay of Bengal reached up to 263,000 MPs/m^3 in water and 815 MPs/kg in sediment.
- Transparent and white MPs dominated, with size <1 mm
- Polyethylene was the most prevalent polymer, followed by PP, PA, PS, and PET.
- Over 75% of water and 83% of sediment sites exceeded extreme pollution thresholds.
- Marine microplastics pathways highlight their transboundary nature, driven by riverine, land-based, oceanic, and atmospheric inputs.

1. Introduction

The rapid growth of plastic production and its widespread use in daily life have led to an alarming rise in plastic pollution across the globe. Among the various forms of plastic debris, microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as a pressing environmental concern due to their persistence, ubiquity, and potential ecological risks [1,2]. Coastal and marine environments are particularly vulnerable to microplastic contamination because of their direct exposure to land-based discharges, riverine inputs, and anthropogenic activities such as fishing, aquaculture, shipping, and tourism [3,4]. The Bay of Bengal, one of the world's largest tropical bays, supports diverse ecosystems, including mangroves, estuaries, coral reefs, and sandy beaches. Many transboundary rivers fall into the bay. Moreover, it also serves as a hub for densely populated coastal communities. This dual role as a vital ecological region and socio-economic resource makes it highly susceptible to microplastic pollution. Coastal areas, particularly estuaries and beaches, act as sinks and pathways for MPs, making the Bay of Bengal a hotspot for marine plastic pollution [5,6].

In aquatic systems, particularly in coastal and marine environments, MPs originate from both primary sources, such as microbeads in cosmetics and industrial abrasives, and secondary sources like fragmentation of larger plastic debris, fishing gear degradation, textile fibers, and packaging materials [7,8]. Once released, MPs are subjected to physical, chemical, and biological processes, and particles are transported, deposited, and resuspended by hydrodynamic processes that influence their transport pathways, from riverine inputs into estuarine mixing zones, coastal sediments, and eventually into the open marine ecosystem [9]. It poses potential risk to plankton, benthic organisms, fish, and higher trophic levels, including humans, through the food chain. Moreover, their persistence and adsorption capacity for persistent organic pollutants, heavy metals, and pathogenic microorganisms amplify their toxicity [10,11].

Microplastics are widely distributed in marine environments, occurring in both the water and sediments. While marine water reflects the transport and dispersion of MPs, sediments often act as a major sink where these particles accumulate over time. Microplastics in the marine environment occur in a wide variety of colors, sizes, shapes, and polymer types. These variations reflect differences in plastic sources, environmental weathering processes, and the degradation of larger plastic debris. The study hypothesizes that smaller-sized, low-density polymers are dominant due to their widespread use, and the occurrence and ecological risk of microplastic pollution are crucial and widespread in the bay.

Although numerous studies worldwide have investigated microplastic abundance, characteristics, and impacts, research in the Bay of Bengal is comparatively limited and fragmented [12,13]. It is difficult to draw consistent conclusions about the level of contamination and its ecological implications from the existing studies. Therefore, a systematic review and quantitative synthesis become necessary to consolidate current knowledge, identify common trends, highlight data gaps, and provide a quantitative synthesis of abundance, types, and risk of microplastics in water and sediment in the Bay's coastal areas. Integrating evidence across islands, estuaries, beaches, and coastal areas enables more holistic and comprehensive understanding of the occurrence, risks, and pathways of microplastics in the Bay of Bengal. The present study aims to analyze available research on microplastic abundance, assess risks through various indices using secondary data from published articles, and pathways in the coastal environments of the Bay of Bengal, which will provide an evidence-based assessment of microplastic pollution in the Bay of Bengal, offering critical insights for policymakers, environmental managers, and regional stakeholders engaged in marine conservation and pollution control.

2. Materials and Methods

2.1. Literature and Data Collection

The literature search was conducted in Scopus, Web of Science, and ScienceDirect databases for studies published between January 2015 and December 2025. The following search string was used in the title, abstract, and keywords fields: ('microplastics' OR 'microplastic' OR 'micro-plastic') AND ('marine' OR 'coastal' OR 'estuary' OR 'beach') AND ('Bay of Bengal' OR 'Bangladesh coast' OR 'Indian coast'). Only peer-reviewed articles published in English were considered. Inclusion criteria included: peer-reviewed articles reporting microplastic abundance in marine water or sediment, studies conducted in the Bay of Bengal region, and studies reporting quantitative data. Studies were excluded if they focused only on freshwater environments, did not report quantitative microplastic data, or were review articles, conference abstracts, or duplicate records. To get additional relevant studies, the reference lists of key publications were also reviewed.

In this systematic review, a predefined protocol was followed to ensure methodological rigor and minimize bias, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P) guidelines [14,15]. A database of potentially relevant articles was compiled based on titles, after which abstracts were screened to exclude those lacking sufficient or relevant information. Full texts of the remaining studies were then assessed, and only relevant articles and substantive data were included in the final quantitative synthesis. The entire selection process is summarized in the PRISMA flow diagram (Figure 1).

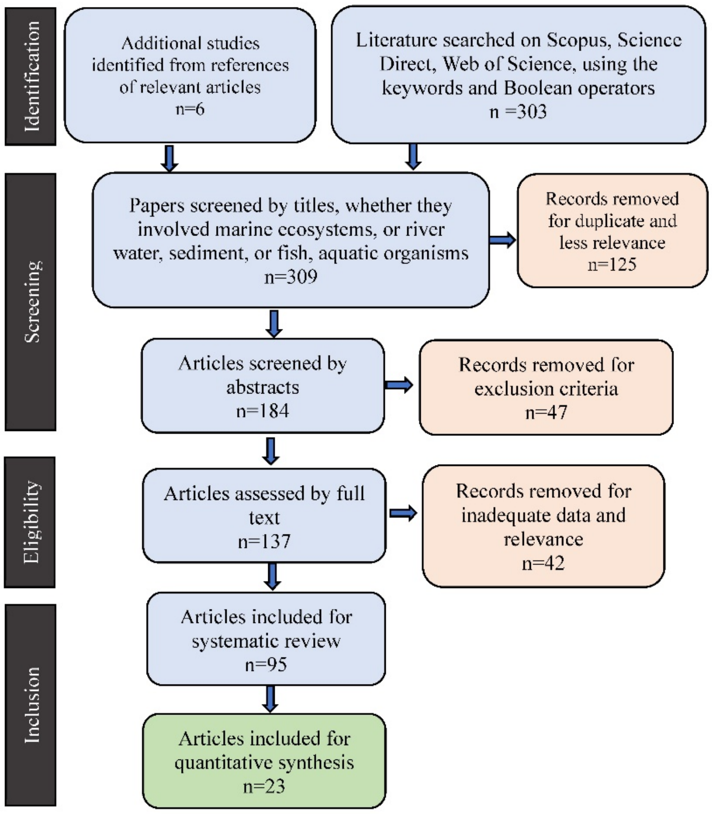


Figure 1. PRISMA diagram of the systematic review and quantitative synthesis.

2.2. Study Area

The Bay of Bengal, located in the northeastern part of the Indian Ocean, represents one of the world's largest coastal ecosystems, which serves as a vital resource for millions of people in the surrounding countries. The northern and eastern coastal regions, particularly along Bangladesh, are distinguished by extensive riverine inputs, including discharge from the Ganges-Brahmaputra-Meghna (GBM) river system, the largest deltaic system globally. These rivers transport massive loads of sediments, nutrients, and anthropogenic pollutants, including microplastics, into the coastal and marine environment. The coastal zones of the Bay of Bengal are not only highly productive fishing grounds but also centers of tourism, shipping, industrial activities, and dense human settlements, all of which contribute to increasing microplastic contamination. The ecological importance and socio-economic dependence of the Bay of Bengal's coastal areas provide a critical significance for assessing the abundance, risks, and pathways of microplastics. Available data on the occurrence of microplastics in the water and sediments of the Bay of Bengal's coastal areas, including beaches and estuaries, were considered in the study (Figure 2). Sediment in this study refers to estuarine and marine bottom sediment (including intertidal and subtidal deposits) reported in the selected studies [13]. Reported concentrations were expressed as MPs/m^3 of water samples and MPs/kg of dry sediment. A total of twenty-six (26) study locations from India (IND) and Bangladesh (BD) were encompassed in this study (Table 1).

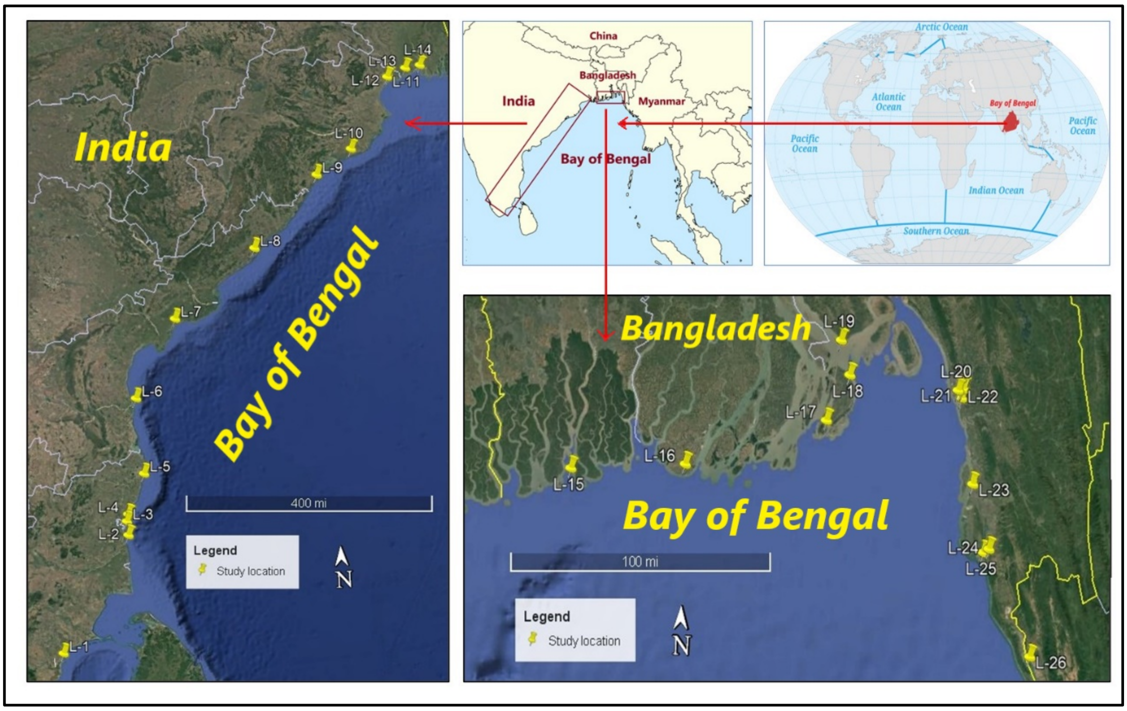


Figure 2. Study locations in the Bay of Bengal.

Table 1. Sampling locations and types of sample in the study area.

Sampling Location	Study Area	Location Characteristics	Sample Type	Reference
L-1	Thoothukudi coast, IND	Port city, fishing	Water and sediment	[12]
L-2	Pichavaram coast, IND	Mangrove forest	Sediment	[16]
L-3	Uppanar and Gadilam estuaries Cuddalore, IND	Industries, fishing	Sediment	[17]
L-4	Ariyankuppam estuary, Puducherry, IND	Mangrove forest	Water and sediment	[18]
L-5	Muttukadu backwater estuary, IND	Tourism	Water and sediment	[19,20]
L-6	Mypadu coast, IND	Tourism, fishing	Water and sediment	[21]
L-7	Manginapudi coast, IND	Tourism	Water and sediment	[21]
L-8	Vizag coast, IND	Port city, tourism	Water and sediment	[21]
L-9	Gopalpur coast, IND	Tourism	Water and sediment	[21]
L-10	Puri beach, IND	Tourism and pilgrimage	Water and sediment	[21,22]
L-11	Chandipur coast, IND	Tourism	Water and sediment	[21,23]
L-12	Budhabalanga Estuary, Chandipur, IND	Fishing	Water	[24]
L-13	Digha Beach, IND	Tourism	Water and sediment	[21,22]
L-14	Hooghly River Estuary, IND	Fishing	Water	[25]
L-15	Pasur and Shela river, BD	Mangrove forest	Water and sediment	[26]
L-16	Kuakata beach, BD	Tourism	Water and sediment	[13,27,28]
L-17	Nijhum Dwip Island, BD	Fishing, tourism	Water and sediment	[29,30]
L-18	Hatiya Island, BD	Fishing, agriculture	Water and sediment	[31]
L-19	Meghna estuary, BD	The biggest estuary in BD, fishing	Water and sediment	[30,32]
L-20	Patenga beaches, BD	Port, tourism	Water and sediment	[33,34]
L-21	Karnaphuli estuary, BD	Port, fishing, industries	Water and sediment	[30,32,35,36]
L-22	Parki beaches, BD	Port, tourism	Water and sediment	[33,34]
L-23	Matamuhuri estuary, BD	Hill tract forest, fishing	Water and sediment	[32]
L-24	Bakkhali estuary, BD	Fishing	Water and sediment	[32]
L-25	Cox's Bazar Beach, BD	Tourism	Water and sediment	[27,30,37]
L-26	Naf estuary, BD	Fishing,	Water and sediment	[32]

2.3. Statistical Analysis

To assess the traits of microplastics in the Bay of Bengal's water and sediment, a resilient statistical framework was utilized on existing secondary data from published studies in the area. At first, Pearson's correlation analysis was used to examine the relationships between microplastic characteristics like shape, color, size, and polymer type. This helped to connect parameters to shared origins or similar environmental behaviors. Next, we applied Principal Component Analysis (PCA) to simplify the dataset and visualize the primary trends in microplastic distribution. The PCA biplot helped to understand how variables and samples clustered together, highlighting the main factors driving variability. Finally, Hierarchical cluster analysis was used to group samples with similar microplastic compositions, which revealed patterns in both their location and makeup. These combined statistical methods provided a solid basis for interpreting the abundance, sources, and distribution of microplastics in water and sediment samples. For these analyses, MS Excel, SPSS 30, and Paleontological Statistics Software were used.

2.4. Risk Assessment

Understanding the environmental risks associated with microplastics goes beyond simply measuring their abundance. The potential impacts on ecosystems and human health are influenced by multiple factors, such as the degree of pollution, the types of polymers present, and their ecological hazards. Relying solely on abundance data does not provide a complete picture of these risks. To address this gap, combined indices like the Pollution Load Index (PLI), Polymer Hazard Index (PHI), and Ecological Risk Index (ERI) are often applied to better evaluate ecological threats [38–40]. In the present study, these three indices, PLI, PHI, and ERI, were employed to assess and compare microplastic-related risks across the selected locations, with the calculated values and corresponding risk categories presented in Table 2 [41–43].

Table 2. Index score and risk levels of microplastic pollution.

PLI Value	Risk Level	PHI Value	Risk Level	ERI Value	Risk Level
<10	Low	0–1	Low	<150	Low
10-20	Medium	1–10	Moderate	150–300	Moderate
20-30	High	10–100	High	300–600	High
>30	Very high	100–1000	Severe	600–1200	Severe
		>1000	Extreme	>1200	Extreme

2.4.1. Pollution Load Index (PLI)

The Pollution Load Index (PLI) is a valuable metric for comparing microplastic contamination levels across different sites or monitoring changes over time. By converting raw abundance data into a single standardized value, it enables the identification of highly polluted areas and supports the prioritization of management efforts [26,44–46]. The index is calculated using the equation:

$$PLI_r = C_i/C_o$$

where PLI_r represents the pollution load index for a given location, C_i is the measured abundance of microplastics, and C_o refers to the baseline abundance level. The lowest abundance of microplastics reported by the studies considered in this synthesis was considered the baseline level [26]. The baseline values were 2.35 MPs/m^3 [19] and 1 MPs/kg [21] for water and sediment samples, respectively.

2.4.2. Polymer Hazard Index (PHI)

The Polymer Hazard Index (PHI) recognizes that different polymers pose varying levels of ecological and health risks. While some plastics are relatively inert, others contain toxic monomers, chemical additives, or have a high capacity to adsorb pollutants, making them more hazardous to organisms and ecosystems. By incorporating the hazard characteristics of individual polymer types, PHI provides a more potent risk evaluation that goes beyond simple counts of microplastic particles [26,44,47]. The index is calculated as:

$$PHI_r = \sum_{n=1}^{n} \left(\frac{Pi}{Ci}\right) \times Si$$

where PHI_r denotes the polymer hazard index, P_i is the abundance of a given polymer type, C_i is the total number of microplastic particles, and S_i represents the risk score assigned to each polymer. Based on Lithner et al. (2011), the S_i values for common polymers are as follows: PP = 1, PE = 11, PAN = 11521, PET = 4, PS = 30, PA = 50, PVC = 5001, ABS = 6552, and EVA = 9 [48]. It should be noted that these hazard scores vary substantially among polymer types and may disproportionately influence the PHI when high-hazard polymers occur even at low abundances. In addition, polymers reported in a generic or uncertain form (e.g., unidentified polymers) were excluded from the PHI calculation to avoid misclassification. Moreover, the hazard scores are based on the chemical properties of virgin polymers and may not fully represent the toxicity of environmentally weathered microplastic particles. Therefore, the PHI results should be interpreted as a relative indicator of potential risk rather than a definitive measure of ecological toxicity.

2.4.3. Ecological Risk Index (ERI)

The Ecological Risk Index (ERI) integrates both the degree of contamination and the hazard score of polymers, offering a more comprehensive assessment of ecological risks. ERI reflects not only how much microplastic pollution is present but also the possible severity of its impacts on organisms and ecosystems. Though this index was originally developed for heavy metal pollution or other classical contaminants, various recent studies widely used this index for microplastic pollution [26,41,49]. The calculation involves three steps:

$$C_f = C_i/C_n$$

$$T_i = \sum_{n=1}^{n} \left(\frac{Pn}{Ci}\right) \times Sn$$

$$ERI_r = T_i \times C_f$$

Here, ERI_r denotes the Ecological Risk Index, C_i and C_n represent the abundance of microplastics in polluted and unpolluted samples, respectively. The contamination factor (C_f) expresses the relative pollution load, while the toxicity coefficient (T_i) accounts for the biological sensitivity and toxicity of different polymers. Ti is obtained by summing the proportion of each polymer type (P_n/C_i) multiplied by its corresponding hazard score (S_n). In this study, the reference value (C_n) used in the calculation of the contamination factor was derived from the lowest abundance of microplastics reported by the studies considered in this synthesis. The C_n values were 2.35 MPs/m^3 [19] and 1 MPs/kg [21] for water and sediment samples, respectively. However, it should be noted that defining a universal background concentration for microplastics is challenging due to spatial variability and differences in sampling and analytical methodologies among studies. Consequently, the ERI values presented in this study should be interpreted as relative indicators of potential ecological risk rather than precise quantitative estimates.

3. Characterization of Microplastics

3.1. Abundance of Microplastics

Microplastics in water and sediment samples of the Bay of Bengal coastal areas, including islands, beaches, and estuaries, were found in a wide range of abundance (Table 3). The compiled data used in this study were obtained from multiple published studies that employed different sampling strategies, analytical techniques, and reporting units. To improve comparability, microplastic abundance values reported in water and sediment were considered separately and standardized to commonly reported units (items m^{-3} for water and items kg^{-1} for sediment). However, variations in sampling methods, size detection limits, and identification techniques (e.g., visual sorting, FTIR, or Raman spectroscopy) among the primary studies may introduce heterogeneity in the dataset. Therefore, the synthesized results should be interpreted with caution, as methodological differences among studies could influence reported abundance and characteristics. The study found the abundance of microplastics ranged from 2.35 to 263,000 MPs/m^3 and 1 to 815 MPs/kg for water and sediment samples, respectively, in the Bay of Bengal coastal areas. The highest abundance of MPs in water (263,000 ± 243,000 MPs/m^3) and sediment (815 ± 158 MPs/kg) samples was recorded in location L-1 (Thoothukudi coast, India), and L-5 (Muttukadu backwater estuary, India), respectively. Among the beaches Puri, Digha, Kuakata, Patenga, Parki, and Cox's Bazar beach, Kuakata showed the highest abundance (145,500 ± 33,100 MP/m^3) of microplastics in water, while Cox's Bazar showed the highest abundance (460 MP/kg) of microplastics in sediment. Various anthropogenic activities, including tourism, fishing, industrial and commercial activities, cause the varying abundance of microplastics.

Table 3. MPs' abundance in water and sediment of the Bay of Bengal.

Study Location	Study Area	MPs in Water (MPs/m^3)	MPs in Sediment (MPs/kg)	Reference
L-1	Thoothukudi coast, IND	263,000 ± 243,000	80 ± 72	[12]
L-2	Southeastern coast of India, Pichavaram, IND	----	460 ± 275	[16]
L-3	Uppanar and Gadilam estuaries Cuddalore, IND	----	43.06	[17]
L-4	Ariyankuppam river estuary, Puducherry, IND	124,830 ± 22,440	136.33 ± 24.75	[18]
L-5	Muttukadu backwater estuary, IND	2.35 195 ± 38	2.85 815 ± 158	[19,20]
L-6	Mypadu coast, IND	93 ± 23	3	[21]
L-7	Manginapudi coast, IND	67 ± 30	6	[21]
L-8	Vizag coast, IND	47 ± 11	5	[21]
L-9	Gopalpur coast, IND	80	6	[21]
L-10	Puri beach, IND	6400 ± 1700 147 ± 12	190.4 ± 28.0 5	[21,22]
L-11	Chandipur coast, IND	---- 60	200 1	[21,23]
L-12	Budhabalanga Estuary, Chandipur, IND	9330 ± 2110 to 28,500 ± 2770	----	[24]
L-13	Digha Beach, IND	5300 ± 1800 67 ± 50	173.4 ± 40.1 2	[21,22]
L-14	Hooghly River Estuary, IND	132.7	----	[25]
L-15	Pasur and Shela river estuary, BD	Pasur: 21.76 ± 12.52 Shela:14.85 ± 6.86	Pasur 82.86 Shela 57.90	[26]
L-16	Kuakata beach, BD	145,500 ± 33,100 85.2 ± 39.2 ---	362.2 ± 57.2 94.8 ± 36.3 232 ± 52	[13,27,28]
L-17	Nijhum Dwip Island, BD	72.83 ± 30.76 105 ± 324.47	138.39 ± 34.15 ---	[29,30]
L-18	Hatiya Island, BD	38.77 ± 10.086	110.90 ± 20.62	[31]
L-19	Meghna estuary, BD	150 ± 65.62 462.9 ± 324.5	30.56 ± 9.34 157.6 ± 89.0	[30,32]
L-20	Patenga beaches, BD	231.11 ± 49.95 ---	--- 86.83 ± 23.48	[33,34]
L-21	Karnaphuli estuary, BD	350 ± 69.22 916.7 ± 462.6 3.99 ----	102.22 ± 40.01 94.3 ± 33.1 ---- 39.2	[30,32,35,36]
L-22	Parki beaches, BD	173.33 ± 49.12 -----	---- 89.17 ± 30.96	[33,34]
L-23	Matamuhuri estuary, BD	318.52 ± 172.09	118.33 ± 26.81	[32]
L-24	Bakkhali estuary, BD	222.22 ± 45.64	115.00 ± 43.28	[32]
L-25	Cox's Bazar Beach, BD	600 101 ± 31.0 ----	190 132 ± 36.8 460	[27,30,37]
L-26	Naf estuary, BD	322.22 ± 206.16	96.67 ± 22.81	[32]

3.2. Colors of Microplastics

In the marine system, microplastics are found in a variety of colors, which indicates their various sources. Figure 3 displays the variation of colors of MPs in the study area. Transparent, white, blue, red, yellow, green, black, violet, and pink colored MPs are commonly reported in the studies. The study observed that 53% and 65% of the studies on water and sediment, respectively, reported that transparent/white colored microplastics were most prevalent in the study area (Tables 4 and 5). Moreover, blue, black, yellow, violet, and red are also found as prevalent colors in some studies. Transparent microplastic particles are often derived from common items such as packaging materials, plastic bags, and water bottles. Similarly, white-colored microplastics are likely to originate from products like plastic bags, disposable cups and plates, packaging materials, buckets, and containers [50,51]. In addition, they can also result from the degradation processes of colored plastics, including weathering and photo-oxidation [52].

Table 4. Dominant colors, sizes, shapes, and polymers of microplastics found in water.

Study Area	Dominant Colors	Prevalent Shapes	Dominant Size	Prevalent Polymers	Reference
L-1	Blue	Fragment (40.89%)	0.5–1 mm (31.11%)	PE (49.83%)	[12]
L-4	-	Fiber (87.9%)	0.5–1 mm	PE	[18]
L-5	Blue (26.88%)	Fragment (48.9%)	0.5–1 mm (50.6%)	PA (38.7%)	[19]
L-5	Blue (33%)	Fiber (38%)	3–5mm (49%)	PE (33%)	[20]
L-6 to L-11, L-13	White	Fragments	4–5 mm	PP	[21]
L-10, L-13	Blue, red	Fibers	<125 µm	Polyesters	[22]
L-12	Black (40%)	Fibers (54.56%)	-	PE	[24]
L-14	White/transparent	Filamentous	0.1–0.2 mm	--	[25]
L-15	Transparent	Fragments	<0.5 mm (32%)	PS	[26]
L-16	Transparent (45.2%)	Fiber (50.1%)	>0.1mm (58.6%)	PE (40.4%)	[13]
L-16, L-25	White	Fiber	0.5–1 mm (33%)	PE (40%)	[27]
L-17	Transparent (62.8%)	Fragments (61.51%)	<0.5mm (83.08%)	PE (57%)	[29]
L-18	Transparent (45.9%)	Fragments (60.6%)	<0.5mm (79.1%)	PP (51%)	[31]
L-19, L-21, L-23, L-24, L-26	Transparent (42.28%)	Fibers (89%)	<0.5 mm (92.93%)	PE (46.43%)	[32]
L-19, L-21, L-25	Black (72.35%)	Fibers (60%)	0.2–0.5 mm (48%)	Semi synthetic polymer (24%)	[30]
L-20, L-22	Violet	Fibers	<0.5 mm	PET (34.89%)	[33]
L-21	White (30%)	Films (26.5%)	1–5 mm (50%)	PET (19%)	[35]

Table 5. Dominant colors, sizes, shapes, and polymers of microplastics found in sediment.

Study Area	Dominant Colors	Prevalent Shapes	Dominant Size	Prevalent Polymers	Reference
L-1	Blue	Fragment (52.72%)	0.5–1 mm (43.96%)	PE (47.58%)	[12]
L-2	Transparent (46.42%)	Fiber (56.9%)	<0.5 mm (81.2%)	PP	[16]
L-3	Red: 30%	Fibers 45%	0.1–1 mm	LDPE (39%)	[17]
L-4	-	Fiber (79.4%)	0.5–1 mm	HDPE, LDPE	[18]
L-5	Black (25.2%)	Fragment (57.6%)	0.5–1 mm (55.0%)	PP (31.65%)	[19]
L-5	Blue (54%)	Fiber (58%)	1–3 mm (59%)	PE (50%)	[20]
L-6 to L-11, L-13	White, transparent	Foam	1–2 mm	PS	[21]
L-10, L-13	Blue, white	Fibers	<125 µm	PP, PS	[22]
L-11	Yellow (29%)	--	1–5 mm (47%)	PET (57%)	[23]
L-15	Transparent	Fragments	4–5 mm	PS	[26]
L-16	Transparent (40%)	Fibers (55%)	1–5 mm (55%)	PET 45.5%	[28]
L-16	Transparent (42.6%)	Fiber (67.9%)	>0.1 mm (51.4%)	PE (40.4%)	[13]
L-16, L-25	White, transparent	Fiber	0.5–1 mm (34%)	PE (40%)	[27]
L-17	Transparent (62.21%)	Fragments 64.05%	<0.5 mm (74.54%)	PE 57%	[29]
L-18	Transparent (51%)	Fragment (64.6%)	<0.5 mm 73.6%	PP (51%)	[31]
L-19, L-21, L-23, L-24, L-26	Transparent (45.22%)	fibers (61%)	<0.5 mm (80.9%)	PE (36.67%)	[32]
L-19, L-21, L-25	Black: 72.7%	Fibers (56%)	0.2–0.5 mm (37%)	Semi-synthetic polymer (31%)	[30]
L-20, L-22	Transparent, white	Fibers, foams	<0.5 mm	PE (33.33%)	[34]
L-21	White (19%)	Films (33.3%)	1–5 mm (30.4%)	PET (27.78%)	[36]
L-25	White (28.55%)	Fiber (28.01%)	<250 µm (43.5%)	PP (24.89%)	[37]

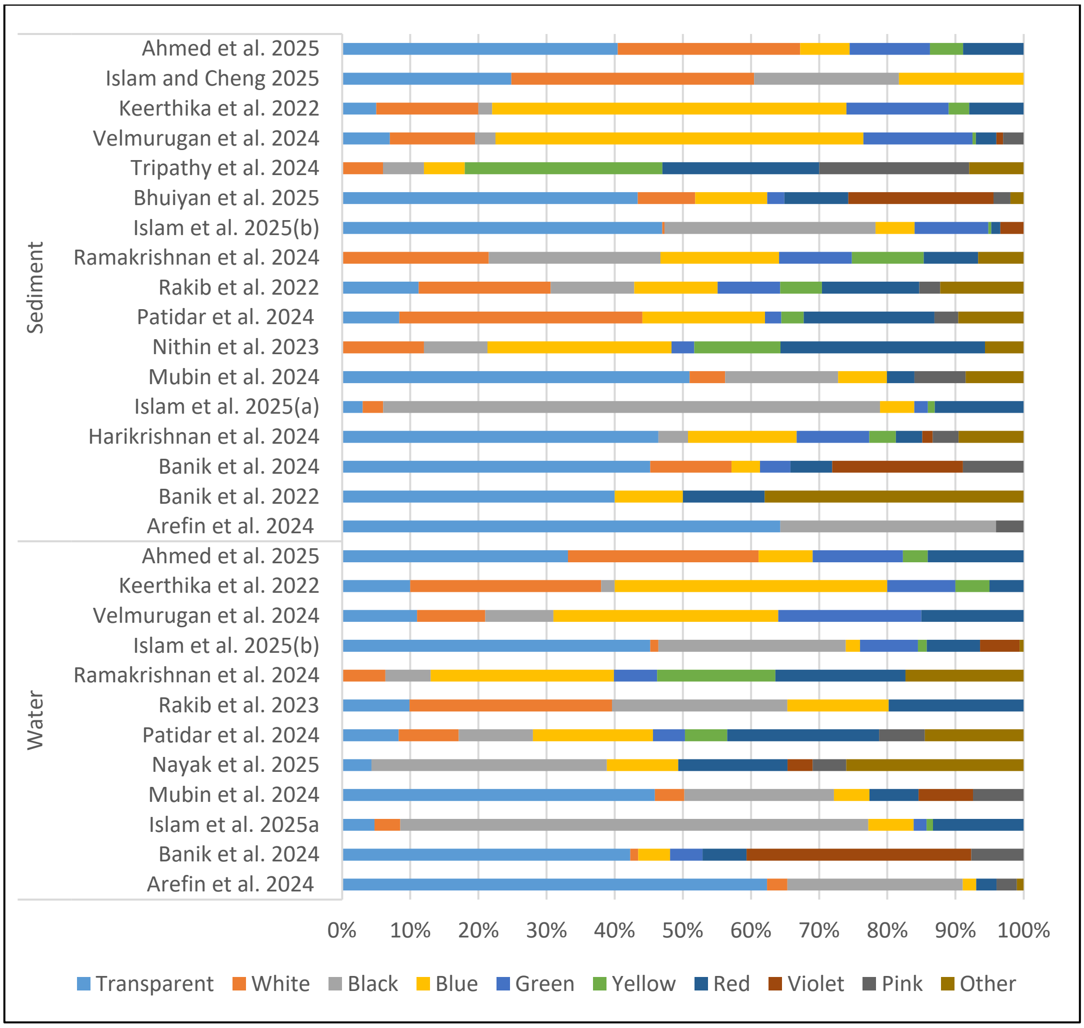


Figure 3. Color variation of MPs in the Bay of Bengal [12,13,16,17,19,20,22–24,26,28–32,34–37].

3.3. Size of Microplastics

Microplastics in the marine ecosystem demonstrate a wide range of sizes. Figure 4 shows the size distribution of MPs in the study area. The study observed that 71% and 65% of the studies on water and sediment, respectively, reported that microplastics with a size of <1 mm were most prevalent in the study area. Besides, microplastics size >1mm are also found as prevalent in several studies (Tables 4 and 5). Small-sized microplastics are often produced from the breakdown of larger plastic items through physical, chemical, or biological processes such as abrasion, weathering, and photo-oxidation [53]. They can also be directly manufactured in tiny forms, such as microbeads in personal care products or pellets used as raw materials in plastic production [54]. Because of their small size, they are easily transported through water, air, and soil, making them more bioavailable to aquatic organisms and even capable of entering the food chain [55].

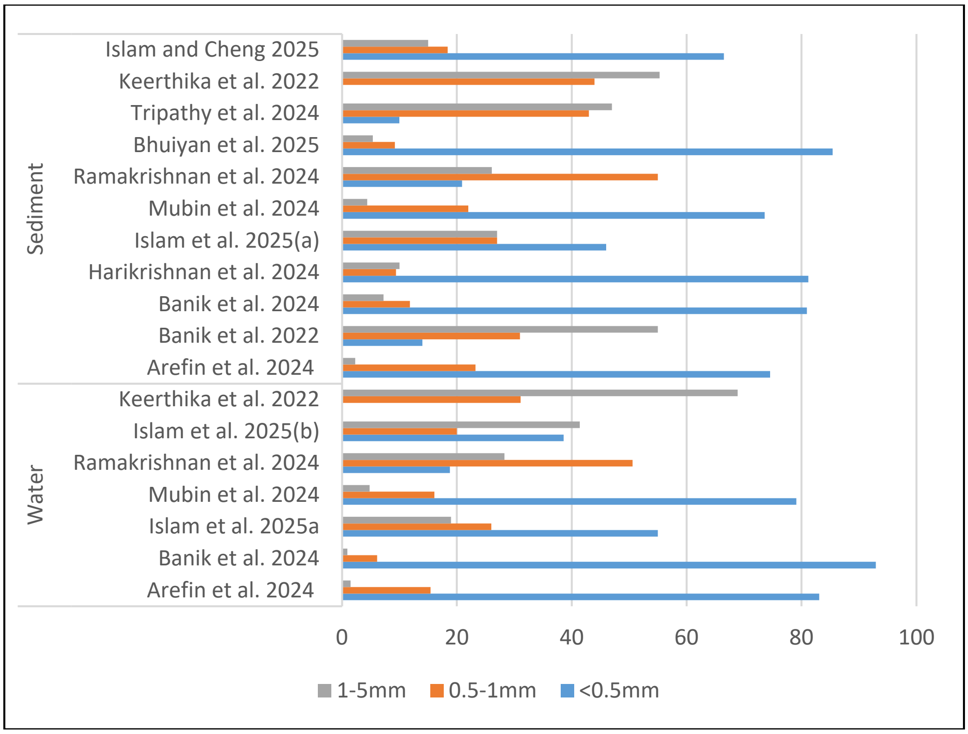


Figure 4. Size distribution of MPs in the Bay of Bengal [12,13,16,19,23,28–32,34,37].

3.4. Shapes of Microplastics

Figure 5 exhibits various MPs' shapes in water and sediment samples of the Bay of Bengal. Microplastics in the marine system are found in a variety of shapes, which reflect their diverse sources and degradation processes. Fibers, fragments, films, foams, and pellets are commonly reported shapes found by the researchers. The study noted that fibers and fragments were the most prevalent microplastics in the study area (Tables 4 and 5). Besides, some studies reported films, and foams as dominant shapes. Fiber-type microplastics are largely linked to synthetic textiles, discarded fishing gear, and industrial discharges, particularly wastewater released from garment and textile industries [56,57]. Fragment-type microplastics are formed when larger plastic debris undergoes degradation by photo-oxidation, mechanical abrasion, and biological breakdown [58,59]. Film-shaped microplastics often originate from packaging materials, plastic bags, construction activities, and agricultural soils, while foam particles typically come from the degradation of larger polystyrene (PS) items, including packaging products and aquaculture floats [60–62].

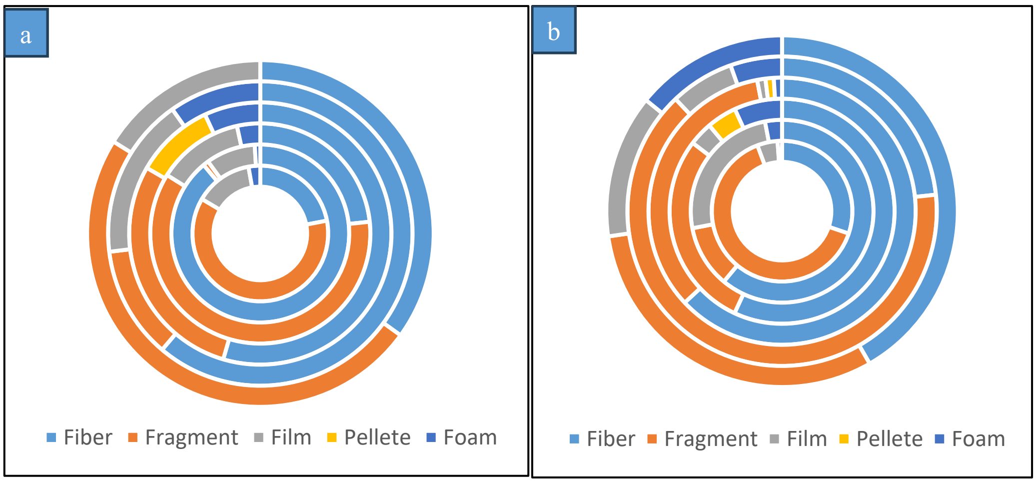


Figure 5. Diversity of shapes of MPs in (**a**) water [19,22,24,29,31,32] and (**b**) sediment [16,22,29–32] of the Bay of Bengal.

3.5. Polymeric Composition of Microplastics

Microplastics in the marine ecosystem are found in various types of polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), nylon/polyamide (PA), polyvinyl chloride (PVC), ethylene vinyl acetate (EVA), and acrylonitrile butadiene styrene (ABS) (Figure 6). It was observed that 47% and 45% of the studies on water and sediment, respectively, reported that polyethylene (PE) was the most prevalent microplastic in the study area. Moreover, some studies reported PP, PA, PS, and PET as dominant polymers (Tables 4 and 5). Polyethylene (PE) and polypropylene (PP) are the most common polymers in microplastic studies, because they are extensively used in packaging, plastic bags, and other single-use consumer products [63,64]. Polyethylene terephthalate (PET) is mostly linked to beverage bottles and textile fibers, whereas polystyrene (PS) typically appears as foam fragments derived from disposable items and packaging materials [65,66]. Polyvinyl chloride (PVC) is mainly associated with construction-related sources such as pipes and cables, and nylon is predominantly found originated from fishing nets, ropes, synthetic fabrics, etc. [67–70]. The types and relative abundance of these polymers in the marine system often depend on local pollution inputs, including industrial effluents, urban runoff, household waste, and fishing activities.

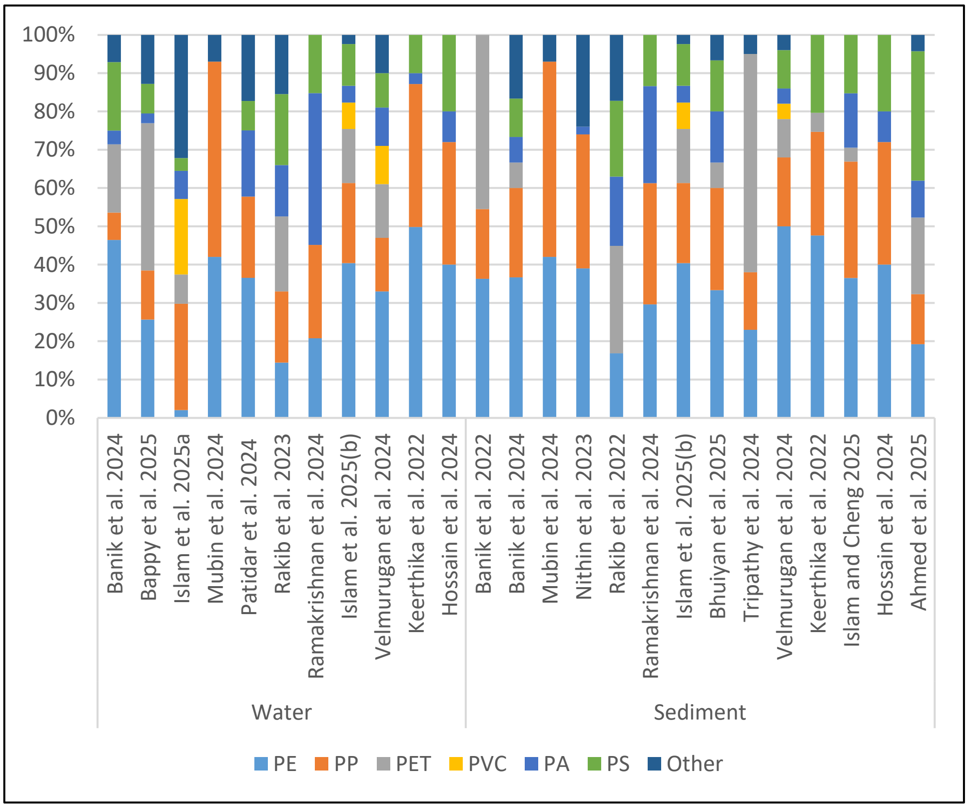
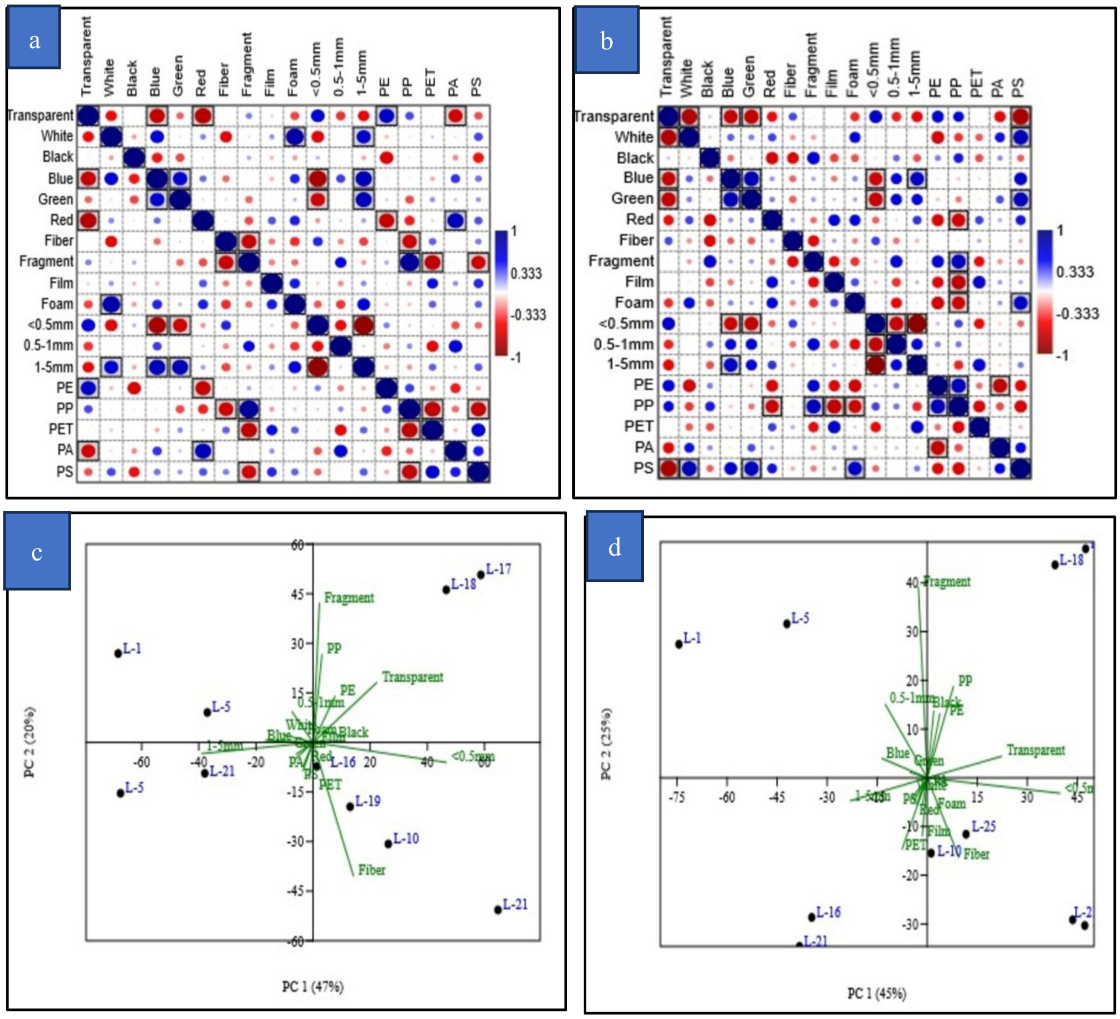


Figure 6. Polymer types of MPs in the Bay of Bengal [12,13,17,19,20,22,23,26–28,30–37].

4. Statistical Analysis

The correlation matrices and multivariate analyses reveal several patterns in the reported characteristics of microplastics in the water and sediment of the Bay of Bengal. However, these relationships should be interpreted cautiously due to the heterogeneous nature of the compiled datasets. The correlation plots (Figure 7a,b) show varying positive and negative associations among microplastic attributes such as color, shape, size classes, and polymer types. Positive correlations between transparent particles and polyethylene (PE), as well as between fragment-shaped MPs and polymers like polypropylene (PP), may suggest common sources and pathways of contamination. In contrast, negative correlations, such as red color and PE polymers, may indicate differing origins and environmental behaviors. Some moderate associations are observed between specific polymer types and particular shapes or colors, which may suggest potential similarities in sources or environmental processing pathways. These patterns may indicate differences in regional environmental conditions and human activities within the Bay of Bengal coastal zone, including riverine inputs, urban discharge, industrial activities, and maritime operations. However, these relationships may also reflect differences in sampling methods, size thresholds, and reporting practices among the individual studies included in the dataset [29,30]. The principal component analysis (Figure 7c,d) further illustrates the distribution of microplastic characteristics, where the first two components explain a considerable proportion of the variance, indicating that size classes, polymer composition, and certain colors contribute to the observed variability. Nonetheless, the clustering of variables around the origin suggests that many characteristics are widely distributed and not strongly separated across samples [29,32]. The hierarchical clustering and heatmap results (Figure 7e,f) provide additional exploratory insight into potential groupings among microplastic attributes, highlighting similarities among certain polymers, shapes, and size fractions. Locations such as L-16, and L-21 clustered closely, suggesting similar microplastic profiles, while L-1 and L-10 formed separate branches, reflecting distinct compositions. Among the categories, fibers, PE, PP, and transparent particles showed relatively higher intensities compared to other types, highlighting their dominance in water samples. For sediment samples, sites such as L-17 and L-18 grouped closely, reflecting similarities in microplastic composition, while L-5 and L-25 showed distinct clustering patterns, suggesting site-specific differences. Polymers like PP and PE, along with fibers, were more prominent contributors compared to other categories such as PET, PA, and PS. Therefore, the observed statistical groupings likely represent general patterns rather than definitive spatial relationships. Overall, these multivariate analyses provide an exploratory overview of patterns in microplastic characteristics across the compiled studies, although the observed relationships should be interpreted with caution given methodological differences and potential reporting biases among the included datasets [30,31].



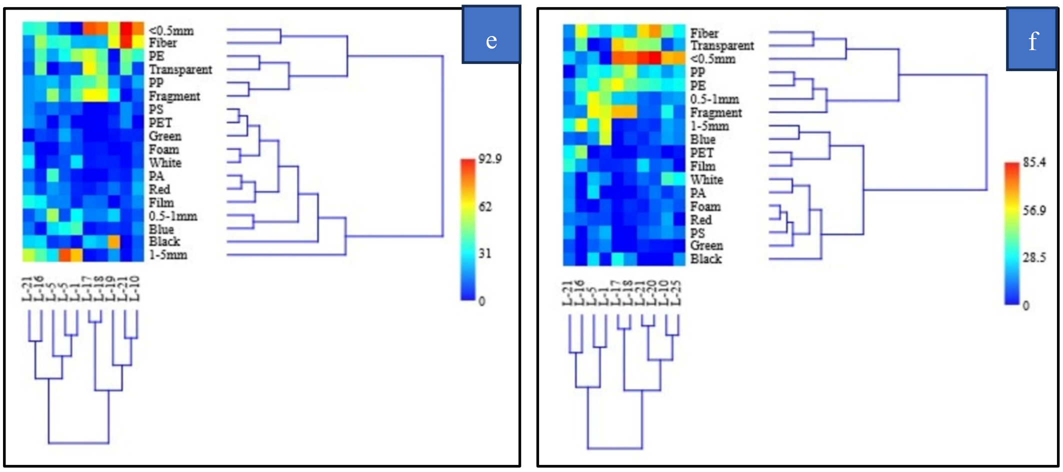


Figure 7. Pearson's correlation analysis of MPs in (**a**) water and (**b**) sediment, PCA analysis of MPs in (**c**) water and (**d**) sediment, and HCA analysis of MPs in (**e**) water and (**f**) sediment of the Bay of Bengal.

5. Risk Assessment

5.1. Pollution Load Index (PLI)

For microplastics in the aquatic system, the Pollution Load Index (PLI) provides a measure of the overall pollution load, enabling comparisons between different locations. A PLI value of 1 generally indicates baseline conditions or negligible pollution, whereas values above 1 signify elevated microplastic contamination. Higher PLI values correspond to more severe pollution, indicating a decline in water quality caused by the presence of microplastics [71–73]. The analysis showed that 75% of the locations (L1, L4, L6, L9, L10, L12–L14, L16, L17, L19–L26) were classified as extremely polluted (PLI > 30), while 8% each were ranked as 'high' (L7, L11), 'medium' (L8, L18), and 'low' (L5, L15) in terms of microplastic pollution in water samples (Figure 8). For sediment samples, 17% of the locations (L6–L9) were found to have low pollution; conversely, 83% of the locations (L1–L5, L10–L11, L13, L15–L26) were classified as extremely polluted with respect to microplastic abundance (Figure 8). The highest PLI values for water (111915) and sediment (815) were found in L-1 (Thoothukudi coast, India) and L-5 (Muttukadu backwater estuary, India), respectively. The analysis suggests that most of the locations of the Bay of Bengal were extremely polluted by various anthropogenic activities, including fishing, tourism, industrial discharge, etc., in terms of microplastic abundance.

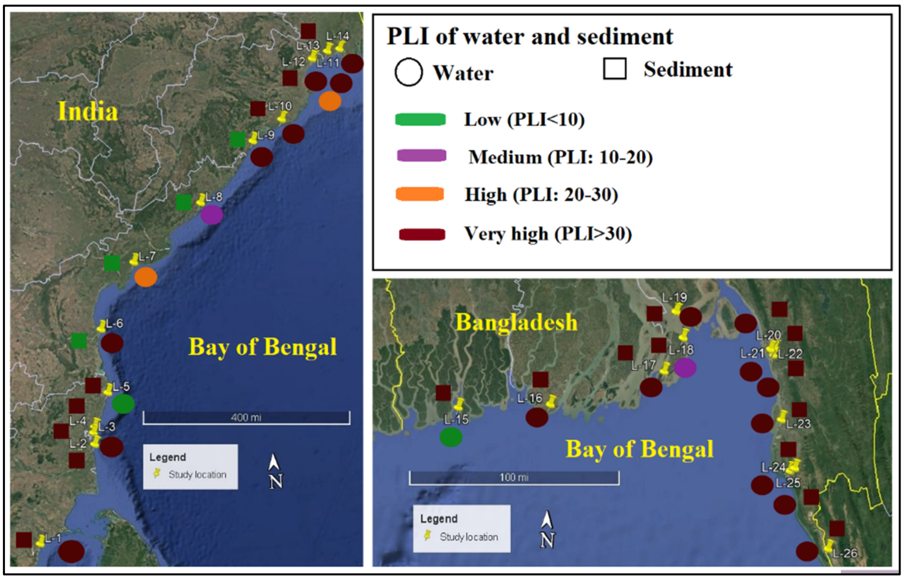


Figure 8. PLI analysis of MPs in water and sediment of the Bay of Bengal.

5.2. Polymer Hazard Index (PHI)

The Polymer Hazard Index (PHI) assesses the potential risks of microplastics in the aquatic system by integrating their relative abundance with the hazard ratings of different polymer types. It provides insight into the possible impacts on both the environment and human health associated with the specific polymers found in the environment [74,75]. The study found that in terms of microplastic pollution and polymer toxicity 36% of the locations (L16, L19–L21) were classified at a 'severe' PHI level and 36% of the locations (L5, L10, L15, L25) were at 'high' level, while 27% of the locations (L1, L17, L18) were ranked as 'moderate' for water samples (Figure 9). However, for sediment samples, 33%, 42%, and 17% of the locations were ranked as 'moderate' (L3, L11, L17, L18), 'high' (L1, L10, L15, L20, L25), and 'severe' (L5, L16), respectively, while one location (L21) was found at the 'extreme' level (Figure 9). The highest PHI values for water (769) and sediment (1103) were observed in L-20 (Patenga beaches, Bangladesh) and L-21 (Karnaphuli estuary, Bangladesh), respectively. This study may indicate that most of the coastal areas have high-risk polymers, which could pose considerable threats to both aquatic ecosystems and human health.

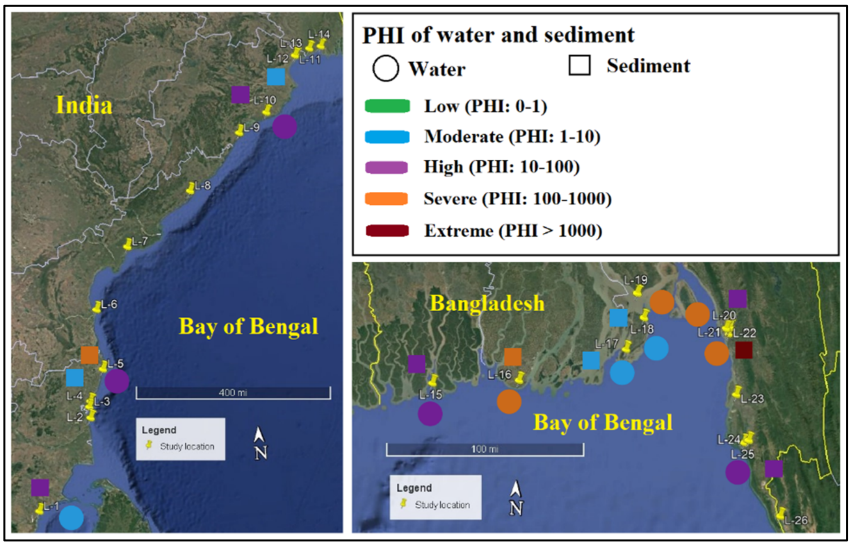


Figure 9. PHI analysis of MPs in water and sediment of the Bay of Bengal.

5.3. Ecological Risk Index (ERI)

Higher ERI values suggest considerable ecological risks, which highlight the significant abundance of toxic polymers [38,76,77]. The analysis revealed that two locations (L5, L18) were classified as 'low' ERI level and two (L15, L17) as 'moderate', while one location (L25) was categorized as 'severe' in terms of microplastics abundance and polymer hazard score. In contrast, 55% of the locations (L1, L10, L16, L19–L21) fell into the 'extreme' ERI level for water samples (Figure 10). For sediment samples, one location (L3) was ranked as 'moderate' and another (L18) as 'high', whereas 25% of the locations (L1, L11, L17) were at the 'severe' level, and 58% (L5, L10, L15, L16, L20, L21, L25) were at the 'extreme' level of ERI value (Figure 10). Location L-16 (Kuakata beach, Bangladesh) and L-5 (Muttukadu backwater estuary, India) for water and sediment samples, respectively, showed the highest ERI values. The analysis suggests that a significant part of the Bay of Bengal faces serious ecological risks from microplastic pollution, which threatens aquatic biodiversity and disrupts ecosystem stability through processes like bioaccumulation and biomagnification.

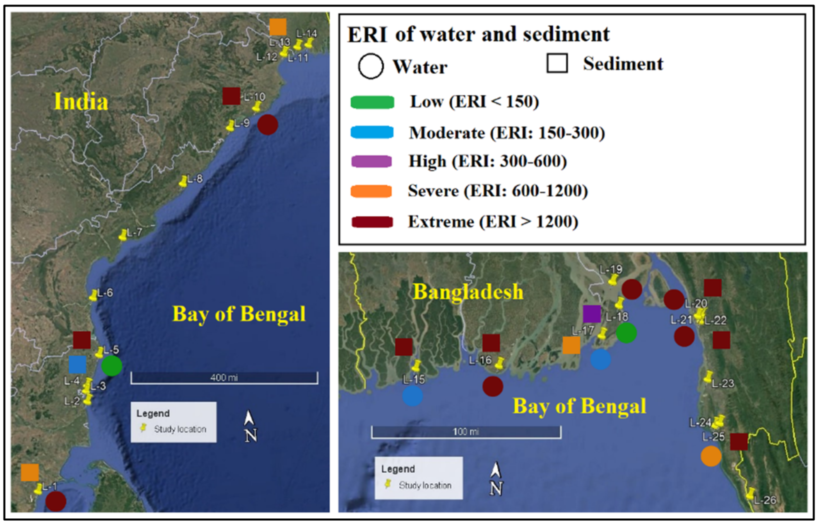


Figure 10. ERI analysis of MPs in water and sediment of the Bay of Bengal.

6. Pathway of Microplastics in the Bay of Bengal

Figure 11 illustrates the multiple pathways through which microplastics (MPs) enter and circulate within the marine environment. River systems function as primary transport routes, carrying MPs from urban runoff and industrial discharges into estuaries and subsequently to the open ocean [78]. Land-based dumping of plastic debris involves the direct disposal of plastic waste from urban, industrial, and domestic sources onto land, which can eventually be carried into rivers and coastal areas. These plastic debris gradually degrade into small plastic particles, which significantly contribute to microplastic pollution, threatening terrestrial and aquatic ecosystems [79,80]. In addition, maritime activities act as a direct source of MPs, as discarded or lost plastic materials from vessels gradually fragment into smaller particles [81,82]. Atmospheric deposition represents another important pathway, where airborne MPs are transported over long distances and eventually settle onto marine surfaces, reflecting the global scale of this issue [83–85]. Once in the ocean, these particles become part of the marine microplastic pool, where they are readily available for ingestion by aquatic organisms. The process of bioaccumulation, particularly in fish, raises critical ecological concerns as MPs accumulate in tissues and may transfer along the food chain [86–88]. Their occurrence along beaches further demonstrates the pervasive distribution of MPs and their interaction with sensitive coastal ecosystems. Overall, the pathway of marine microplastics emphasizes the interconnected and transboundary nature of microplastic pollution, with inputs from urban riverine discharge, land-based, oceanic, and atmospheric sources contributing to their widespread presence. Addressing this challenge requires coordinated strategies aimed at reducing emissions across all major entry pathways.

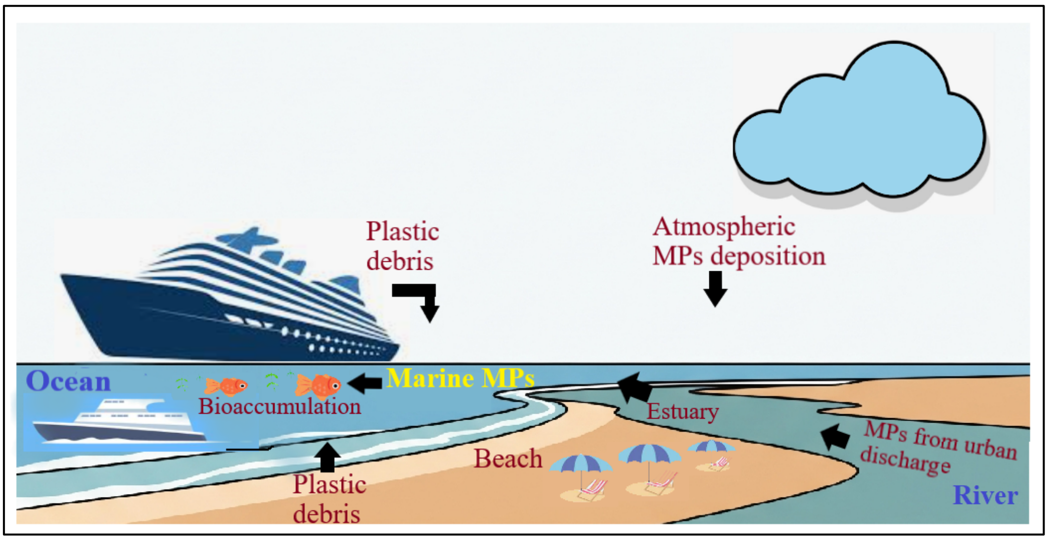


Figure 11. Pathway of microplastics in the Bay of Bengal.

7. Discussion

The results indicate that microplastics (MPs) are widely distributed in the coastal environments of the Bay of Bengal, including beaches, islands, and estuarine areas. The abundance of MPs in water ranged from 2.35 to 263000 MPs m^{-3}, while sediment samples contained 1 to 815 MPs kg^{-1}, showing substantial spatial variation among locations. In several coastal regions globally, like the Persian Gulf coast, Iran, Padang beach, Indonesia, Beibu Gulf, China, Danish coastal area, the abundance of microplastics varied from 0.064 to 87 MPs/m^3 and 0.151 to 155 MPs/kg in water and sediment samples, respectively [89–92]. Therefore, the analysis found that the abundance of MPs in water and sediment samples in various locations of the Bay of Bengal was comparatively high due to extensive riverine discharge and various anthropogenic activities in the study area. The highest abundance of MPs in water (263,000 MPs m^{-3}) and sediment (815 MPs kg^{-1}) samples was recorded at location L-1 (Thoothukudi coast, India) and L-5 (Muttukadu backwater estuary, India), respectively, due to intense anthropogenic activities such as industrial discharge, port operations, fishing activities, and urban wastewater inputs. In addition, estuarine hydrodynamics and riverine transport in these regions facilitate the accumulation and retention of plastic debris, which gradually fragments into microplastics within the coastal environment. Moreover, it was observed that studies conducted at the same sites have reported inconsistent levels of microplastics abundance [19–22]. This highlights the need for standardized global methods to ensure that assessments of MPs are more consistent, reliable, and allow for meaningful comparisons across different research efforts. The characteristics of MPs further provide insight into their sources and environmental behavior. Transparent and white particles were the most frequently reported colors, suggesting that common consumer plastics such as packaging materials, plastic bags, and bottles are major contributors. The predominance of particles smaller than 1 mm may indicate extensive fragmentation of larger plastic debris through physical and photochemical degradation processes. In terms of shape, fibers and fragments were dominant, which are typically associated with textile fibers, fishing gear, and the breakdown of larger plastic items. Polyethylene (PE) and polypropylene (PP) were the most commonly identified polymers, which may reflect their widespread use in single-use plastic products and packaging materials. Arat 2024 also reported PE and PP polymers as dominant microplastics in the marine environment [2]. The statistical analyses conducted in the study provide exploratory insights into potential relationships among different microplastic characteristics [93]. The correlation matrices reveal both positive and negative associations among variables such as polymer type, shape, color, and size fractions. For instance, the positive correlation observed between transparent particles and polyethylene may reflect the widespread use of transparent polyethylene packaging materials. Similarly, associations between fragment shapes and polypropylene polymers may indicate the degradation of rigid plastic products commonly made from polypropylene. However, these relationships should be interpreted cautiously due to methodological differences among the compiled studies. Overall, the high pollution load and ecological risk indices may suggest that microplastic contamination poses considerable environmental risks to the Bay of Bengal coastal ecosystem. Liu et al. 2024 also found moderate ecological risk of MPs in the Shenzhen coastal ecosystem [94]. Microplastics enter the marine environment through multiple interconnected pathways, including riverine transport of urban and industrial waste, land-based plastic dumping, maritime activities, and atmospheric deposition, which collectively contribute to their widespread distribution in coastal and oceanic systems [95]. The Bay of Bengal receives massive freshwater discharge from several major rivers such as the Ganges, Brahmaputra, and Meghna, which carry large volumes of land-based plastic waste into coastal waters. Consequently, riverine transport represents a major pathway for microplastic input into the marine environment of this region. Once introduced into marine waters, these particles can accumulate in sediments and organisms, leading to bioaccumulation through the food chain and posing potential ecological risks to marine ecosystems.

8. Limitations of the Study

Despite providing a regional overview of microplastic contamination, this study has several limitations. The dataset was compiled from previously published studies that used different sampling strategies, size ranges, extraction methods, and polymer identification techniques. These methodological differences may affect the reported abundance and characteristics of microplastics in both water and sediment. In addition, variations in detection limits and selective reporting among studies may influence the observed distributions of polymer types, colors, shapes, and size classes. As a result, the correlations and multivariate patterns identified in this study should be interpreted with caution, since they may partly reflect differences in analytical methods rather than true environmental relationships. Furthermore, the compiled data represent different locations and sampling periods, which may also contribute to variability in the results. Therefore, the findings should be considered as general regional trends rather than precise quantitative comparisons. Future studies using standardized sampling protocols, consistent size thresholds, and harmonized analytical techniques would greatly improve the reliability and comparability of microplastic research in the Bay of Bengal region.

9. Conclusions

This study provides a comprehensive assessment of microplastic contamination in the coastal regions of the Bay of Bengal, highlighting both their abundance and associated ecological risks. The synthesized data indicate that microplastic concentrations reported in the literature vary widely, ranging from 2.35 to 263,000 MPs m^{-3} in marine water and from 1 to 815 MPs kg^{-1} in sediment. Some locations, such as the Thoothukudi coast (263,000 MPs/m^3 in water) and the Muttukadu backwater estuary (815 MPs/kg in sediment), reported comparatively higher concentrations in the reviewed studies. The analysis of physical characteristics revealed that transparent and white microplastics were most dominant in 53% of water and 65% of sediment samples of the reviewed studies, which may have originated from packaging, plastic bags, and other disposable products. Other prevalent colors included blue, black, yellow, violet, and red. Size distribution showed dominance of particles smaller than 1 mm, reported in 71% and 65% of the reviewed studies on water and sediment, respectively, which may indicate extensive degradation and persistence of plastics in the marine environment. In terms of morphology, fibers and fragments were the most prevalent shapes, reported in the reviewed studies, with possible sources being synthetic textiles, packaging items, discarded fishing gear, and industrial wastewater discharges from garments and textile industry. Among polymer types, polyethylene (PE) was most frequently observed, reported in 47% and 45% of the reviewed studies on water and sediment, respectively, followed by polypropylene (PP), polyamide (PA), polystyrene (PS), and polyethylene terephthalate (PET). These polymers are consistent with the widespread use of packaging materials and single-use plastics. Statistical analyses, including Pearson's correlation matrices, PCA, and hierarchical cluster analysis, suggest co-occurrence patterns influenced by diverse sources and environmental processes. Risk assessments revealed alarming levels of contamination. For water, 75% of locations exceeded the extreme pollution threshold (PLI > 30), while for sediment, this figure was even higher at 83%. PHI results suggested the widespread presence of high-risk polymers, posing threats to aquatic organisms and potentially to human health. ERI values further emphasized the severity, with 55% of water and 58% of sediment samples falling into the extreme ecological risk category. It should be noted that the synthesized datasets originate from different studies that may vary in sampling methods, size thresholds, extraction procedures, and polymer identification techniques, which may influence the combined study, comparison, analysis, and indexing. However, the findings may suggest that large parts of the Bay of Bengal are under significant ecological stress from microplastic pollution, which can disrupt food webs and threaten ecosystem stability through processes such as bioaccumulation and biomagnification. In summary, the study demonstrates that the Bay of Bengal faces widespread and crucial microplastic contamination, driven by both local and transboundary sources, including riverine discharge, land-based inputs, maritime activities, and atmospheric deposition. Addressing this pressing challenge requires urgent regional cooperation, proper waste management practices, and targeted policies to reduce plastic debris at its sources. Without integrated action, the ecological health of the Bay of Bengal and the livelihoods of communities depending on it remain at considerable risk.

Author Contributions

M.S.Z.S: conceptualization, methodology, software, data curation, visualization, writing—original draft preparation; M.G.M.: investigation, supervision, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used for the writing of this review article are available from online sources. The raw version of the analysis will be provided upon formal request to the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly to check grammar and spelling for the clarity of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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