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Seasonal assessment and characterization of microplastics in two urban (Balu) and peri-urban (Shitalakshya) rivers of Bangladesh

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This study presents a comprehensive assessment of microplastic (MP) contamination in the Shitalakshya and Balu Rivers, analyzing abundance, characteristics, and seasonal variations in both water and sediment compartments. Sediment samples showed significantly higher concentrations than water samples, with the Balu River exhibiting greater pollution levels (dry season: 5673.33 ± 762.17 MPs per kg; wet season: 3438.33 ± 328.83 MPs per kg) compared to the Shitalakshya River (dry: 3894.1 ± 388.17 MPs per kg; wet: 2671.6 ± 287.33 MPs per kg). Water samples exhibited seasonal fluctuations, with the Shitalakshya showing increased MP abundance during wet seasons (4.65 ± 0.56 MPs per L) while the Balu demonstrated opposite trends. Size distribution analysis revealed dominance of <0.1 mm particles, while morphological characterization identified fragments (53.78–95.36% abundance) and transparent particles as most prevalent. Fourier-transform infrared spectroscopy identified polyethylene as the dominant polymer (56–82%), followed by polypropylene and polyvinyl chloride. Scanning electron microscopy revealed advanced weathering in sediment-derived MPs, featuring cracks and surface erosion indicative of prolonged environmental exposure. Pollution Load Index values (1.34–3.19) classified both rivers as low risk (Category I), though notably lower than regional urban waterways. These findings establish critical baseline data on MP pollution in these economically and ecologically significant rivers, highlighting the urgent need for improved waste management strategies and regulatory frameworks to address plastic pollution in the freshwater ecosystems of Bangladesh.

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1 Introduction

Microplastic pollution has become a significant global concern in the modern world. The increasing use of plastics has led to a daily rise in pollution rates. Global production of plastic products reached 1.7 million tons in 1950, and by 2018, it had increased to 359 million tons.[1] This rise in plastic production indicates a growing threat of microplastic pollution. Since microplastics originate from plastic products, they are formed when plastic fragments are continually broken down into smaller plastic particles through physical, chemical, photolytic, and microbial processes.[2] The polymer structure of plastic degrades in sunlight, reducing the molecular mass of the polymer. Additionally, waves and friction alter the shape and size of plastics in water.[3] Plastics smaller than 5 mm are typically classified as microplastics.[4] MPs vary based on size, shape, color, polymer type, and origin (primary and secondary).[5] Primary microplastics originate from industrial emissions and plastic dust released from products.[6] Secondary microplastics are formed when larger plastic items break down into tiny pieces due to weathering. The most documented types of microplastics worldwide include pellets, fragments, and fibers. Other significant contributors include films, ropes, filaments, sponges, foams, rubber, and microbeads, though in decreasing order of importance.[7] Common polymer types of MPs are polyethylene, polypropylene, polystyrene, and polyvinyl chloride, which are fundamental components of plastic products.[8]

MPs have emerged as prominent aquatic pollutants because they can accumulate, persist in the environment for long periods, and interact with both living and non-living environments.[9] The surface of microplastics can adsorb heavy metals, antibiotics, persistent organic pollutants (POPs), and may serve as transport vectors for toxins.[8] Several environmental and health issues are linked to microplastic presence, including mistaken ingestion, clogging of feeding organs in aquatic organisms,[10] as well as neurotoxicity, oxidative stress, metabolic disorders, immune responses, and damage to development and reproduction.[11]

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However, in the context of Bangladesh, the scenario of MP pollution is particularly concerning because river water is vital for domestic, agricultural, and industrial use, yet it has been critically impacted for an extended period. Significant pollution incidents have been documented in the peripheral waterways surrounding Dhaka city over the past 40 years.[12] With a population of nearly 16 million, the capital city of Bangladesh, Dhaka, is among the most congested cities in the world. It is encircled by several rivers, including the Turag, Balu, and Shitalakshya, and is situated on the northern bank of the Buriganga River. Most industries are located near or on the banks of these rivers, significantly contributing to water pollution. According to several reports, the Buriganga, Shitalakshya, Balu, and Turag Rivers are extremely polluted due to various human activities along their courses. Near these rivers in Dhaka City are three main areas known as Hazaribagh, Tejgaon, and Dhaka-Narayanganj-Derma Dam areas, which are home to almost 7000 industries.[13] Approximately 60 000 m^3 of toxic waste is dumped into the Buriganga and its connected rivers, Turag, Balu, and Shitalakshya, each day, mostly from large industrial clusters.[14]

Although plenty of research has been conducted on microplastics in rivers across the globe, the situation is quite different in Bangladesh. Knowledge regarding the presence and impact of microplastics in Bangladeshi river water remains inadequate, especially in the Shitalakshya and Balu Rivers. On the other hand, drinking water for over 10.2 million people in Dhaka City[15] is mostly sourced from the Saidabad Water Treatment Plant Phase 1 (SWTP-1), Saidabad Water Treatment Plant Phase 2 (SWTP-2), and Padma Water Treatment Plant (PWTP). The raw water sources for SWTP-1 and SWTP-2 are the Shitalakshya River.[16] Consequently, the absence of data about the abundance of MPs in the river hinders efforts to mitigate the MP issue in drinking water. Additionally, it is also important to understand how the abundance of MPs changes in different seasons and locations. The assessment should not be limited to water; riverbank sediment is equally important because sediments are rich in organic substances and minerals[17] and are used to increase soil fertility.[18] However, the presence of MPs in soil may impact the physiology and metabolism of plants.[19]

Challenges persist in developing universally standardized methods for MP extraction and quantification. Thus, a comprehensive approach to studying pollution in the Balu and Shitalakshya Rivers will provide sufficient information to determine the sources and pathways of MPs. This information will be instrumental in developing guidelines and regulations to reduce MP pollution, implementing effective waste management strategies, encouraging sustainable practices, and reducing MP release at its origin.[20–22] Hence, the study focuses on the quantification and identification of MPs in the Balu and Shitalakshya Rivers across different seasons and locations.

2 Materials and methods

2.1 Study area

Dhaka is the capital of Bangladesh and one of the most populated cities in the world. Dhaka resides in the GPS coordinates of 23.811056° N and 90.407608° E. In Bangladesh, June is the warmest month with an average of 28.68 °C and 367.91 mm precipitation, January is the coldest month with an average temperature of 18.75 °C and 10.14 mm precipitation.[23] Around and inside Dhaka, there are a lot of industries, and most of the industries operate near the rivers that connect Dhaka, *e.g.*, Buriganga, Turag, Balu, Shitalakshya, and Dhaleshwari. Among all the rivers, Shitalakshya is an important source of drinking water supply for Dhaka city, and Balu is a tributary of Shitalakshya. Site selection was primarily guided by the Department of Environment's (DoE) established sample collecting sites and on-site field inspections. To monitor the quality of surface water, the Department of Environment has set up a thorough monitoring network. This network comprises the monthly collection of samples from designated sampling points that are strategically positioned along the network's river segments. Water and sediment samples were collected from six different point locations in the Shitalakshya River and six different point locations in the Balu River (Fig. 1). The general location of the sampling sites was expressed using the following naming convention: First Letter of the river with a distinguished middle letter (*e.g.*, BL or SL) _Sampling Station Number (*e.g.*, 1, 2, 3) (Table S1) for the dry season at the start of February 1 and 2. For the wet season, samples were collected in September 2024.

2.2 Sample preparation and isolation

2.2.1 Sample collection. All samples were collected from the designated sampling points (Fig. 1). A total of 48 samples were collected across both seasons. We collected the surface water using a 5-liter stainless-steel bucket, with 100 L of water filtered at each sampling point through a plankton net (50 μm pore size). The retentate was transferred to amber glass bottles and sealed with caps. To prevent contamination, distilled water was used for all cleaning procedures, including the plankton net and bucket. We wore cotton clothing during fieldwork and avoided the use of plastic-based materials (*e.g.*, synthetic gloves) to minimize airborne fiber contamination. Additionally, at least 200 g of riverbank sediment was collected from each point using a shovel (2–3 cm deep from the surface) to assess current microplastic loads in the surface. Sediment samples were placed in glass beakers covered with aluminum foil and stored at 4 °C before processing within 24 hours of collection.

2.2.2 Sample processing and MP isolation from water. Collected samples were filtered again using stacked 4.75 mm (No. 4) and 45 μm (No. 325) stainless steel mesh sieves. Due to the unavailability of a 5 mm sieve, a 4.75 mm (No. 4) sieve was used to remove large MPs. The solids retained on the No. 325 sieve were transferred to a 500 mL glass beaker using a spatula. The sieve was rinsed with a minimal amount of distilled water to ensure complete material transfer. The sample was then dried at 60 °C until constant weight was achieved. After drying, 20 mL of aqueous 0.05 M Fe^{2+} and 20 mL of 30% H_2O_2 were added to the beaker. To minimize sample loss, the beaker was placed in a water bath as the reaction between H_2O_2 and organic matter caused vigorous boiling up to 75 °C. The beaker was continuously stirred on a temperature-controlled magnetic

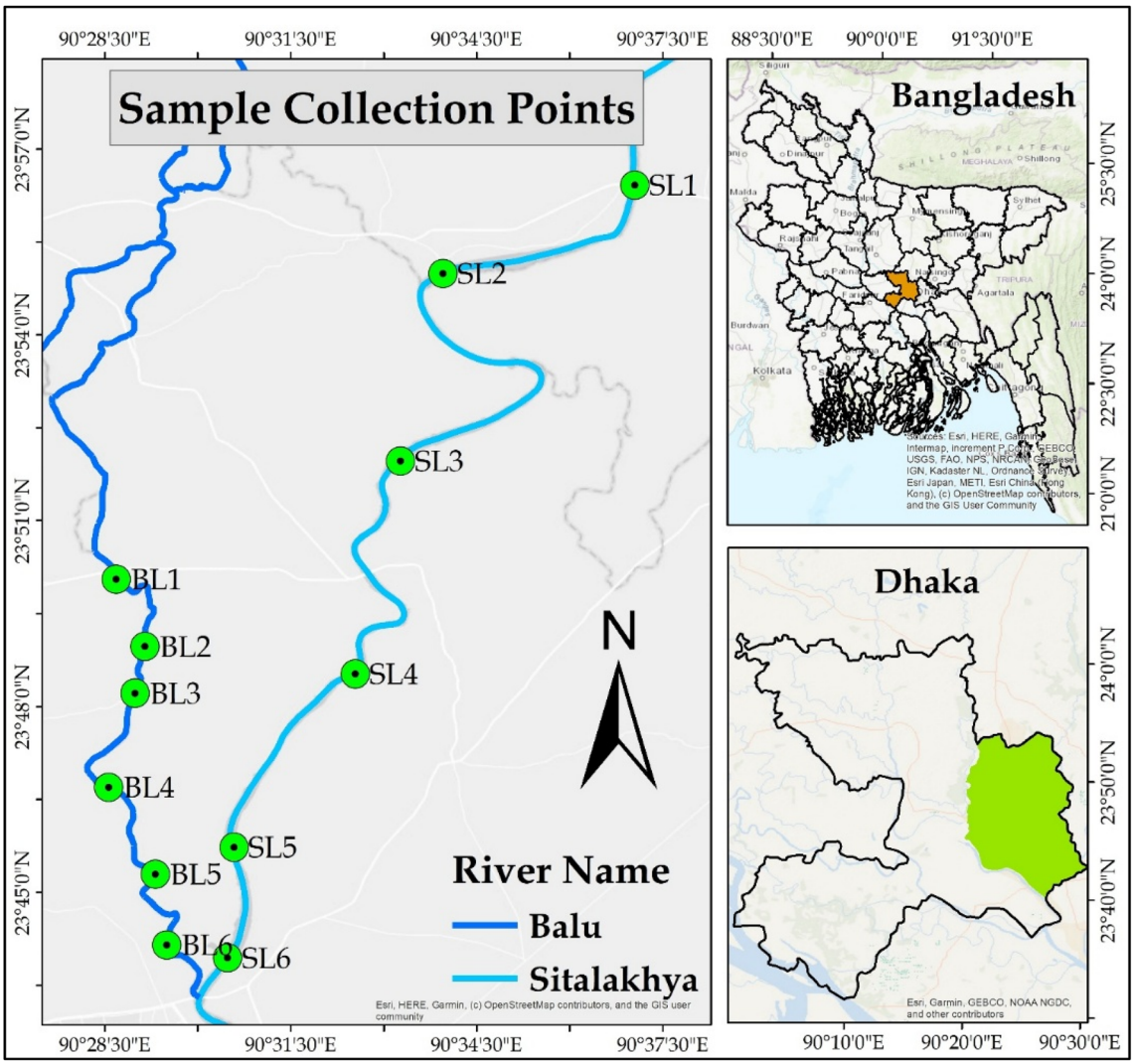

Fig. 1 Sampling locations in the Shitalakshya and Balu Rivers.

hotplate to facilitate mixing and reaction. Heating continued at 75 °C for 30 minutes, with an additional 20 mL of 30% hydrogen peroxide added if any organic matter remained visible. After complete oxidation of the organic matter, NaCl was added at a concentration of 0.3 g per mL of solution to reach a final concentration of 5 M. The wet peroxide oxidation (WPO) solution was transferred to a density separator and left undisturbed overnight for density separation. The settled solids were dried, and any MPs that remained in the solids were separated using forceps, followed by microscopic separation. Microplastic particles floated to the surface, forming a distinct layer, while denser inorganic material settled at the bottom. The floating layer containing MPs and some salt solution was carefully collected into a clean beaker. The collected supernatant was filtered through a 0.45 μm Sartorius cellulose nitrate filter using a vacuum filtration setup. The separated MPs were stored in clean, moisture-free vials. The effective lower detection limit for water samples in this study is 50 μm. Particles smaller than 50 μm in the water column were not consistently captured by our field sampling and are not represented in the reported water abundances. The complete water sample processing method is illustrated in Fig. S1.

2.2.3 Sample processing and MP isolation from sediments. Sediment samples were transferred to glass beakers and dried in an oven at 60 °C until constant weight was achieved. The dried samples were homogenized by grinding with a mortar and pestle. For organic matter digestion, 80 mL of 20% H_2O_2 was added to 200 g of homogenized sediment. The mixture was stirred and maintained at 75 °C for 30 minutes in a water bath.[24–26] Following complete oxidation of organic matter, a 5 M NaCl solution was added to the beaker, mixed thoroughly with the sediment, and allowed to settle for 24 hours. After the settling period, the settled solids were dried and any MPs that remained in the solids were separated using forceps, followed by microscopic separation. The supernatant was carefully decanted into a clean beaker and filtered through a 0.45 μm Sartorius cellulose nitrate membrane. The filter paper was then oven-dried, and MPs were quantified under a microscope and

photos were taken. Then the microplastics were carefully scraped from the filter paper and transferred to labeled glass vials for further analysis. Further particles were measured using ImageJ; these procedures permit detection down to 1 μm. However, extraction and optical identification of very small particles are technically challenging and recovery efficiency in the 1–50 μm size class is lower, so abundances of the smallest particles should be interpreted with caution. The complete sediment sample processing method is illustrated in Fig. S2.

2.3 Visual identification of MP

MPs retained on Sartorius cellulose nitrate filters were examined using a camera-mounted microscope (Nikon Eclipse E100; magnification: 4×, 10×, 40×). Initial identification of MPs was performed based on color and morphological characteristics, with enumeration conducted *via* the camera system. Photomicrographs were captured for subsequent size measurement using ImageJ software (version 1.54g). To ensure counting accuracy, each sample was analyzed in triplicate, enabling the determination of measurement variability.

2.4 Characterization of MP

Fourier-transform infrared spectroscopy (FTIR) was employed for polymer identification. Spectra were acquired using a Thermo Fisher Scientific Nicolet iS5 FTIR spectrometer (4000–500 cm^{-1} range) with samples mounted on a diamond crystal. Spectral comparisons with reference polymer libraries enabled material identification. For surface morphology characterization, scanning electron microscopy (SEM) was performed using a Zeiss EVO18 system (magnification: 500–11 000×; acceleration voltage: 10 kV). Samples were prepared by mounting dehydrated specimens on carbon conductive tape affixed to SEM stubs. Multiple imaging positions were examined to ensure representative morphological characterization.

2.5 Quality control measures

Strict contamination control protocols were implemented throughout the study. All laboratory procedures utilized glassware exclusively, with no plastic materials employed. Glassware was meticulously cleaned with distilled water and then dried in an air dryer before use. Field sampling employed stainless steel scoops and glass bottles to minimize plastic contamination. All experimental work was conducted in a clean bench environment to reduce airborne contamination risks. Sample processing was carefully controlled to preserve microplastic integrity. Drying temperatures were maintained below 70 °C to prevent polymer deformation. During digestion processes, temperature regulation was achieved through a water bath system to avoid thermal degradation of MPs. Glass-coated magnetic stir bars were used instead of polytetrafluoroethylene-coated alternatives to eliminate potential contamination from stir bar wear particles. Separation procedures employed glass beakers and aluminum foil coverings to prevent cross-contamination. The density separator apparatus was thoroughly rinsed with distilled water between samples to minimize carryover effects. Method validation included blank tests with distilled water, which confirmed the absence of microplastic contamination,[27] ensuring the reliability of experimental results. Analytical precision was enhanced through triplicate counting of all samples, reducing quantification errors. These comprehensive quality assurance measures ensured the validity of microplastic identification and quantification throughout the study.

2.6 Pollution load index (PLI)

The Pollution Load Index (PLI) is extensively employed to estimate the ecological risk in aquatic environments, including sediments and surface water.[28] The formula for evaluating PLI utilizing MP abundance is as follows:[29]

$$C_{\mathrm{Fi}} = \frac{C_i}{C_{\mathrm{oi}}} \quad (1)$$

$$\mathrm{PLI} = \sqrt{C_{\mathrm{Fi}}} \quad (2)$$

$$\mathrm{PLI}_{\mathrm{zone}} = \sqrt[n]{\mathrm{PLI}_1 \times \mathrm{PLI}_2 \times \mathrm{PLI}_3 \times \ldots \times \mathrm{PLI}_n} \quad (3)$$

where, C_{Fi} is the contamination factor. C_i is the abundance of MP at the ith sampling site. C_{oi} is the background value.

However, a key challenge in applying PLI to microplastics is the scarcity of actual background values in the literature and the lack of a standardized assessment method. To address this, the current study utilized proxy background concentrations derived from the lowest MP concentrations reported in a related regional study.[30] Thus, in the study, the lowest detected values were adopted as reference concentrations without pristine background data for the study areas. Specifically, for the Shitalakshya River samples, $C_{\mathrm{oi(sediment)}}$ = 875 MPs per kg, $C_{\mathrm{oi(water)}}$ = 2 MPs per L and for the Balu River samples, $C_{\mathrm{oi(Sediment)}}$ = 515 MPs per kg, $C_{\mathrm{oi(water)}}$ = 2 MPs per L.

3 Results and discussion

3.1 Quantification of MPs

From Fig. 2, MP pollution in the Balu River is more severe than in the Shitalakshya River. Additionally, the total number of MPs found per kg of dried riverbank sediment is much higher than the number of MPs found per liter of surface water because MPs can persist in sediments for extended periods. While MPs can be subject to resuspension into the water column under specific hydrodynamic conditions, they predominantly remain buried in the sediments for a long time. Algae, bacteria, and other biological materials can coat microplastics. This phenomenon increases their weight, which may enhance the likelihood that microplastics will stay longer in sediments.

MP abundance in the Shitalakshya River is presented in Tables S2 and S3. In the dry season, MPs abundance varies from 3065 ± 399 MPs per kg to 4595 ± 483 MPs per kg in riverbank sediments, compared to the wet season, where an overall decrease in MPs was found, ranging from 875 ± 52 MPs per kg to 4880 ± 654 MPs per kg. Although an overall decrease was observed, the SL-6 sediment sample showed a higher MPs abundance during the wet season. In the wet season, the concentration was 4880 ± 654 MPs per kg, compared to its dry

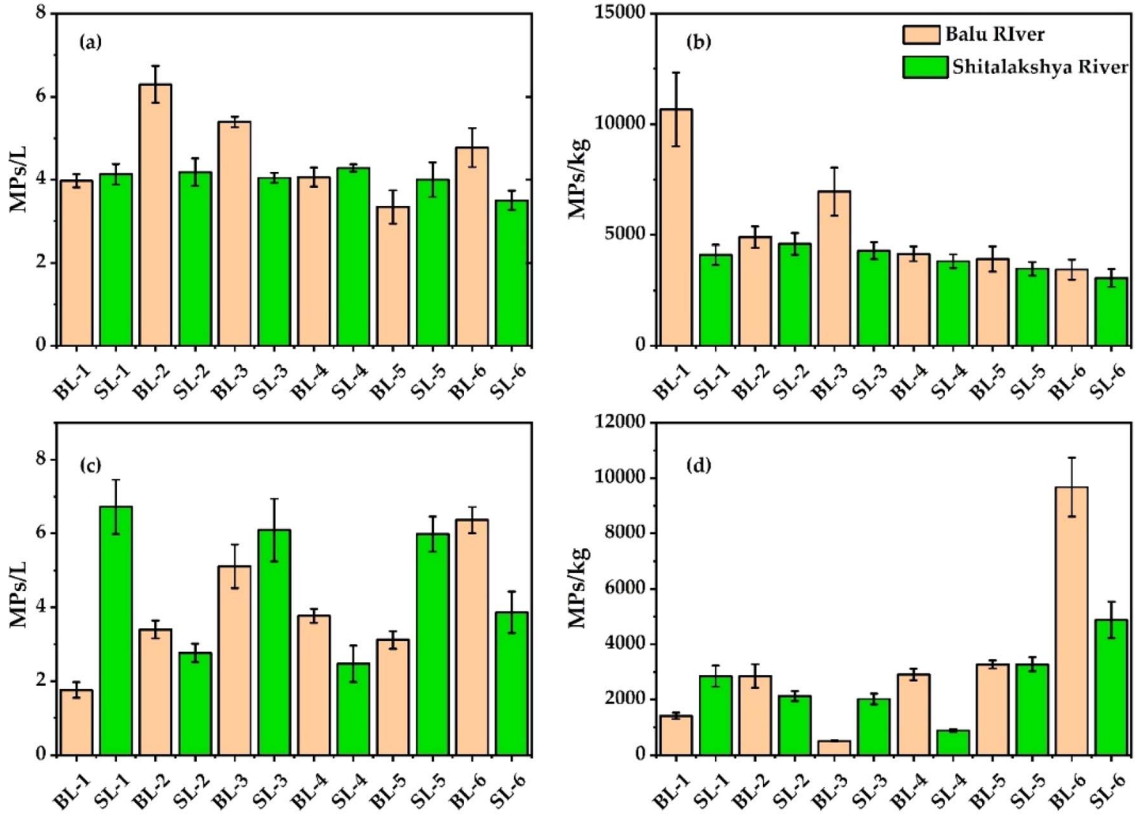

Fig. 2 Seasonal variations of MPs abundance in the Balu and Shitalakshya Rivers. (a) Water samples in the dry season, (b) sediment samples in the dry season, (c) water samples in the wet season, (d) sediment samples in the wet season.

season counterpart, 3065 ± 399 MPs per kg, representing a 59.22% increase. Sampling point SL-6 consists of a small berth, a local market, and small waste dumps adjacent to the berth. During the wet season, the berth experiences heightened human activity and logistical traffic for goods and personnel. This leads to the common practice of direct disposal of various waste materials (*e.g.*, plastic packaging, polybags, organic refuse) into the river. These activities increased anthropogenic pressure, which is the reason for finding the high density of MPs observed during the wet season instead of the dry season. We observed similar trends in the corresponding water sample from SL-6, which further indicates the influence of localized anthropogenic inputs. However, no consistent correlation in MPs abundance was found in sediment samples and water samples across all sampling points and seasons. Similarly,[31] reported significant spatial variability in MPs abundance from one sampling point to another in the Buriganga River.

Conversely, water samples from the Shitalakshya River showed a different result: mean abundance found in the dry season was 4.022 ± 0.24 MPs per L, which increased to 4.65 ± 0.56 MPs per L in the wet season. Thus, an overall increase in MP concentration was observed in the wet season compared to the dry season. However, a notable reduction in MP abundance was observed in the SL-1, SL-3, and SL-5 water samples during the wet season compared to the dry season, with decreases of 62.71%, 50.74%, and 49.5%, respectively. In contrast, the Balu River exhibited a different pattern for all samples, with MP concentrations declining during the wet season across most sampling sites. However, BL-6 was an exception. At this location, the sediment sample showed a 180.8% increase, and the water sample a 33.33% increase in MP abundance during the wet season compared to the dry season. BL-6 is situated at the confluence where the Balu meets the Shitalakshya River and is located near SWTP-1. The area surrounding BL-6 includes local Jamdani production houses (GI product of Bangladesh), local bazar, plastic recycling mills, and small industrial facilities. These are the major contributors to MP accumulation at that site.

Furthermore, our findings indicate that all sediment samples from the Balu River across both seasons consistently exhibited higher MP concentrations than those from the Shitalakshya River. However, no similar trend was observed for water samples during the wet season. Several factors may contribute to these observed differences. River length could play a role; the Balu River is 44 km long, while the Shitalakshya River is 110 km long. River morphology and length can significantly impact the transport and distribution of MP. Moreover, one-way ANOVA revealed a significant difference in MP abundance between sediment and water samples within the Shitalakshya River for both seasons. For the wet season, the difference was significant ($F = 23.15$, $P = 0.0007 < 0.05$), and for the dry season, it was also significant ($F = 292.16$, $P = 9.91 \times 10^{-9} < 0.05$). Similarly, for the Balu River, a significant difference in MP abundance was observed between sediment and water samples

when analyzed by one-way ANOVA for both the wet season ($F = 7.96$, $P = 0.018 < 0.05$) and the dry season ($F = 25.70$, $P = 0.0005 < 0.05$). On the other hand, a comparison of sediment samples between the Shitalakshya and Balu Rivers in the wet season reveals no significant difference in MP abundance ($F = 0.57$, $P = 0.47 > 0.05$). Moreover, additional ANOVA revealed no significant difference in MP abundance when comparing Shitalakshya sediment samples to Balu sediment samples in dry season ($F = 2.43$, $P = 0.15 > 0.05$) and in wet season ($F = 0.57$, $P = 0.47 > 0.05$), nor when comparing water samples between the two rivers in dry season ($F = 1.84$, $P = 0.20 > 0.05$) and in wet season ($F = 0.69$, $P = 0.43 > 0.05$). Similarly, a one-way ANOVA ($F = 2.44$ and $P > 0.05$) revealed no significant relationship between MP abundance and sample collection areas in the Balu River,[32] attributed to the numerous pollution sources, which are contributing factors to MP pollution. A MANOVA was conducted to examine the effect of river type on MP abundance in both sediment and water samples. The analysis revealed that river type had no statistically significant effect ($F = 1.4779$, $P = 0.2520 > 0.05$) on overall MP abundance. Similarly, MP abundance in sediment and water was not significantly affected by seasons ($F = 1.5309$, $P = 0.2406 > 0.05$), based on the MANOVA. Thus, the MANOVA indicated that neither season nor rivers exerted a statistically significant effect on the overall MP abundance in sediment and water when considered together. Besides, Pearson's correlation analysis revealed no statistically significant relationship between water and sediment MP abundances in either season. In the dry season, Pearson's $r = 0.16$ ($p = 0.61$), while in the wet season, Pearson's $r = 0.38$ ($p = 0.25$). These results indicate that water and sediment concentrations varied independently, indicating differences in deposition, transport, and retention mechanisms. The relatively large standard deviations observed at several sites (*e.g.*, BL-1 dry season sediments) likely reflect the heterogeneous nature of MP deposition in dynamic river systems. Localized pollution events, variable hydrodynamic conditions, and micro-scale differences in sediment composition may all contribute to this variability. Moreover, Buriganga, Balu, Shitalakshya, and Turag are the low-flow rivers in Dhaka Division and are habitats for numerous industries, commercial plants, and are connected to sewage and drainage systems; all of which contribute various pollutants to these rivers.[33] Therefore, it is concluded that, based on the findings, MP pollution is mostly influenced by local pollution sources.

3.2 Comparison of MP abundance in the river with other rivers of the Indian subcontinent

In the present study, we compared our findings with relevant previous studies on MP abundance in other rivers within the Indian subcontinent and major global rivers. Direct comparison of all results is challenging due to considerable variations in methodologies, including sampling protocols, extraction techniques, and the investigated size range of MPs. Recognizing these limitations, the comparative analysis primarily focused on rivers situated in similarly populated and industrial geographic areas to provide more contextual relevance. For instance, a recent study on MP abundance in Subarnarekha and Kharkai rivers in Jamshedpur reported 9.55 ± 4.87 MPs per L in water samples and 270.88 ± 105 MPs per kg in sediment samples.[34] This study utilized NaCl (3.5 M) for MPs separation and covered a size range of MPs from 125 μm to 5 mm. In contrast, a study on the Ganga River[35] investigated a wide MP size range (63 μm to 5 mm) and employed saturated $ZnCl_2$ for MP separation, reporting significantly higher MP abundance compared to the Jamshedpur Rivers. Furthermore, the Buriganga River study[36] reported MP abundance ranging from 17.3 ± 1.5 to 133.6 ± 5.5 MPs per kg, with a relatively narrower range of MPs (300 μm to 5 mm). Similarly, the study on the Turag River covered the same range,[37] and this restricted size assessment likely contributed to the lower reported MP abundances. In a global comparison, microplastic (MP) concentrations observed in the Shitalakshya and Balu Rivers represent some of the highest reported levels in the literature. For example, the Yangtze River Estuary, China, documented intermediate levels of 0.5–10.2 MPs per L in water and 20–340 MPs per kg in sediment, with analyzed particle sizes ranging from 500 μm to 5 mm (water) and 48.5 μm to 5 mm (sediment). Other Southeast Asian rivers also exhibit significant MP loads, such as the Saigon River in Vietnam showed notably high sediment concentrations (9167 ± 4559 MPs per kg), exceeding those of other rivers in Table 1, though its water MP abundance was lower. Similarly, the Citarum River, Indonesia, reported 12 ± 6 MPs per m^3 in water and 500 ± 304 MPs per kg in sediment. In contrast, European rivers generally show lower MP abundance. Specifically, the Elbe River, Germany, recorded 5.57 ± 4.33 MPs per m^3 in water and 2080 ± 4670 MPs per kg in sediment. Further, the Antua River, Portugal, showed MP concentrations ranging from 58–1265 MPs per m^3 in water and 18–629 MPs per kg in sediment, with both European studies encompassing a broad size range of MPs (125 μm to 5 mm) in their analyses. The elevated levels observed in the Shitalakshya and Balu rivers, when placed together with these diverse global findings, clearly demonstrate that these systems not only manifest significant local pollution pressures but also substantially contribute to the universal narrative of microplastic contamination in heavily urbanized and industrialized river basins across Asia. These comparisons unequivocally underscore the transboundary significance of MP pollution and strongly highlight the urgent need for coordinated management strategies.

In contrast, the current study covered a wider range for MP analysis (50 μm to 5 mm for water samples, 1 μm to 5 mm for sediment samples). This comprehensive approach, particularly the inclusion of smaller size fractions, contributed significantly to the higher observed MP abundance in the samples. The MP abundance found in Balu River sediment samples was 4555.83 ± 545.5 MPs per kg, and in the Shitalakshya River sediment samples, it was 3282.92 ± 337.75 MPs per kg. The MP abundance reported here for the Balu and Shitalakshya Rivers is among the highest reported for riverine systems, as summarized in Table 1. One of the merits of the current study is its extensive coverage of the size range of MPs for sediment samples. To enable the quantification of the smaller particles, a cellulose nitrate filter (0.45 μm) was used for filtration, and

Table 1 Microplastic studies in freshwater environments and their sampling method, size, and polymeric composition in water and sediments

River	Sample type and sampling instrument	Size range	Abundance	Polymer	Reference
Ganga River, India	Sediments, steel spoon	63 μm to 5 mm	99.27–409.86 MPs per kg	PE, PP, PS, PET	35
Jamshedpur, India	Water, stainless steel bucket	<125 μm to 5 mm	9.55 ± 4.87 MPs per L	PE, PP, PVC, PE, PS, PA	34
	Sediment, shovel		270.88 ± 105 MPs per kg		
Yangtze River Estuary, China	Water, pump	500 μm to 5 mm	0.5 to 10.2 MPs per L		38
	Sediment, box corer	46.8 μm to 5 mm	20 to 340 MPs per kg	PE, PP, PET, PS, rayon	39
Elbe River, Germany	Water, Plankton Net	125 μm to 5 mm	5.57 ± 4.33 MPs per m^3	PE, PP, PS	40
	Sediment, Van Veen Grab		2080 ± 4670 MPs per kg		
Antua River, Portugal	Water, Motor water pump	50 μm to 5 mm	58–1265 MPs per m^3	PE, PP, PS, PET	9
	Sediment, Van Veen Grab		18–629 MPs per kg		
Chao Phraya River (Thailand)	Sediement		62 ± 11 MPs per kg	PE, PP, PS, polybutylene,	41
	Water		80 ± 60 MPs per m^3	and PU, *etc.*	
Citarum River (Indonesia)	Sediment		500 ± 304 MPs per kg	PP, PE	
	Water		12 ± 6 MPs per m^3		
Saigon, Vietnam	Sediment		9167 ± 4559 MPs per kg	PP, PE, PET, PS	
	Water		68 ± 20 MPs per m^3		
Buriganga River, Bangladesh	Water, stainless steel mug	300 μm to 5 mm	4.3 ± 0.5 to 43.6 ± 0.5 MPs per L	PP, PE, PS, PVC, PET, PES, PA	36
	Sediment, scoop		17.3 ± 1.5 to 133.6 ± 5.5 MPs per kg		
Karnaphuli River Estuary, Bangladesh	Sediments, Ekman dredge	250 μm to >5 mm	22.29–59.5 MPs per kg	PE, PS cellulose, PA (nylon), PET	42
Karnafully River, Bangladesh	Surface sediment, Ekman grab sampler	80 μm to 4.69 mm	477.04 ± 112.02 MPs per kg	PE, PET, rayon, PA/nylon, PP	43
	Water, bulk containers with plankton net (20 μm)	40 μm to 3.08 mm	2.11 ± 1.15 MPs per L		
Turag River, Bangladesh	Sediment, stainless-steel scoop	300 μm to 5 mm	19.2 particles per kg	PE, PP, PET, PS, PA	37
Shitalakshya River, Bangladesh	Water, stainless-steel bucket	20 μm to 5 mm	4.34 ± 0.40 MPs per L	PE, PP, PET, nylon, PVC	This study
	Sediment, stainless-steel shovel	1 μm to 5 mm	3282.92 ± 337.75 MPs per kg	PE, PP, PET, nylon, PVC	
Balu River, Bangladesh	Water, stainless-steel bucket	20 μm to 5 mm	4.26 ± 0.30 MPs per kg	PE, PP, PET, nylon, PVC	This study
	Sediment, stainless-steel shovel	1 μm to 5 mm	4555.83 ± 545.5 MPs per kg	PE, PP, PET, nylon, PVC	

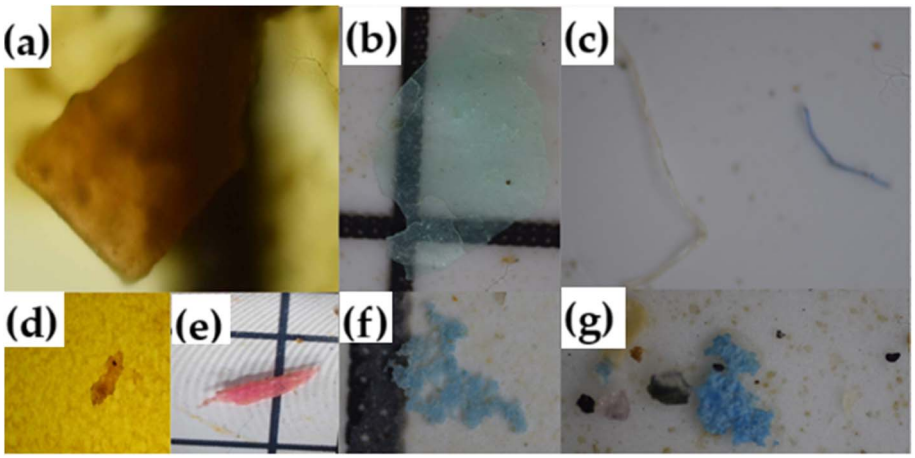

Fig. 3 Different types of microplastic: (a) film type, (b) fragments type, (c) fiber type, (d) fragments type, (e) fragments type, (f) Foam type, and (g) all types.

particle size measurements were conducted using ImageJ software. Regarding polymer composition, the types identified across the compared river systems exhibited general consistency, with PE, PP, and PVC being the most frequently detected polymers.

3.3 Shape of MP

The study identified microplastics (MPs) exhibiting diverse shapes, colors, and sizes. Morphological analysis categorized MPs into three primary types: fragments, fibers, and pellet particles (Fig. 3). Although film-type MPs represent a distinct category, they were classified as fragments in this study due to the predominance of particles smaller than 0.1 mm, where reliable differentiation between films and irregular fragments becomes challenging.

Fragment-shaped MPs dominated all samples from both rivers, representing 53.78% of particles in SL-3 water samples (dry season; Fig. 5a) and reaching 95.36% in BL-6 sediment samples (wet season; Fig. 4d). Even at minimum observed levels, fragments consistently accounted for over 50% of total MP abundance. These irregular particles typically originate from degraded hard plastic products through mechanical, UV, or chemical processes, with common associated polymers

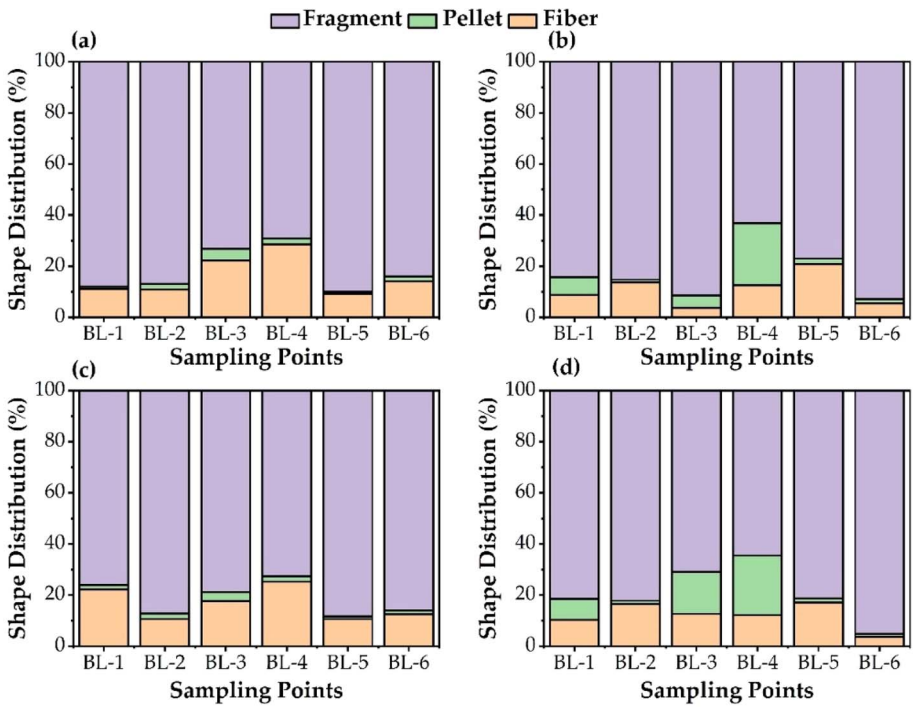

Fig. 4 Shape distribution of MPs in the Balu River samples: (a) dry season water samples; (b) dry season sediment samples; (c) wet season water samples; (d) wet season sediment samples.

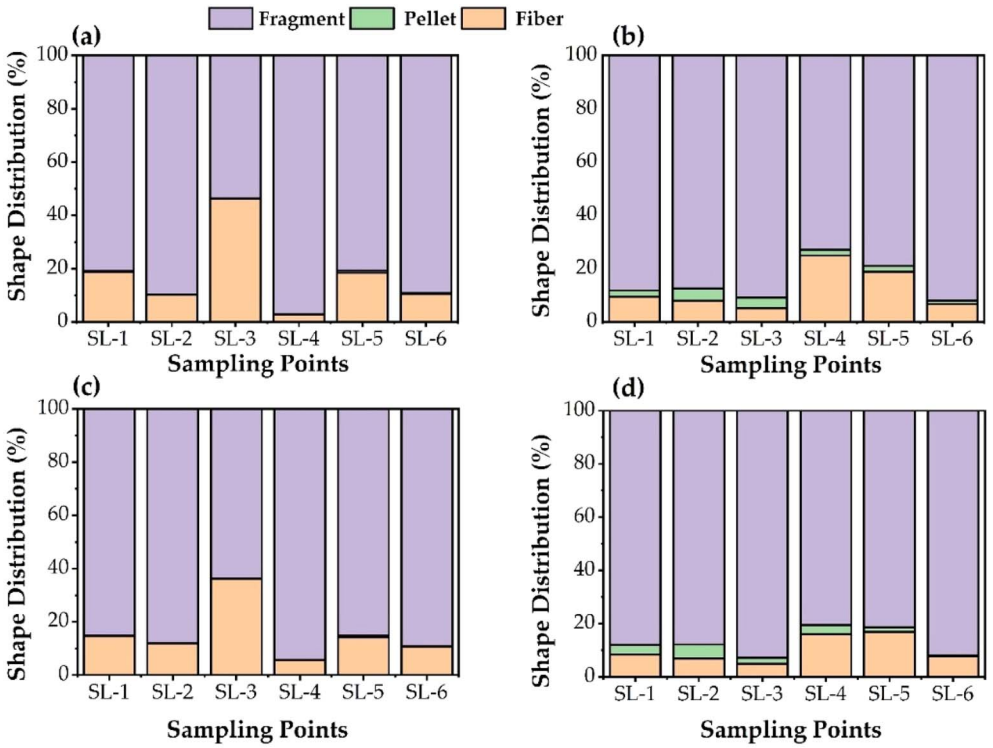

Fig. 5 Shape distribution of MPs in the Shitalakshya River samples: (a) dry season water samples; (b) dry season sediment samples; (c) wet season water samples; (d) wet season sediment samples.

including PE (HDPE and LDPE), PP, and PVC.[44] These findings align with previous observations in the Turag River sediments.[37]

Pellet-type MPs occurred least frequently, ranging from complete absence to a maximum of 23.41% in Shitalakshya River samples (Fig. 5). Fibers showed consistent presence across all samples, though at lower abundances than fragments. The highest fiber concentration (46.22%) occurred in SL-3 water samples (dry season; Fig. 5a), primarily composed of PS, PP, and nylon-type plastics.[45] Fiber prevalence was notably higher in water samples regardless of river or season, likely originating

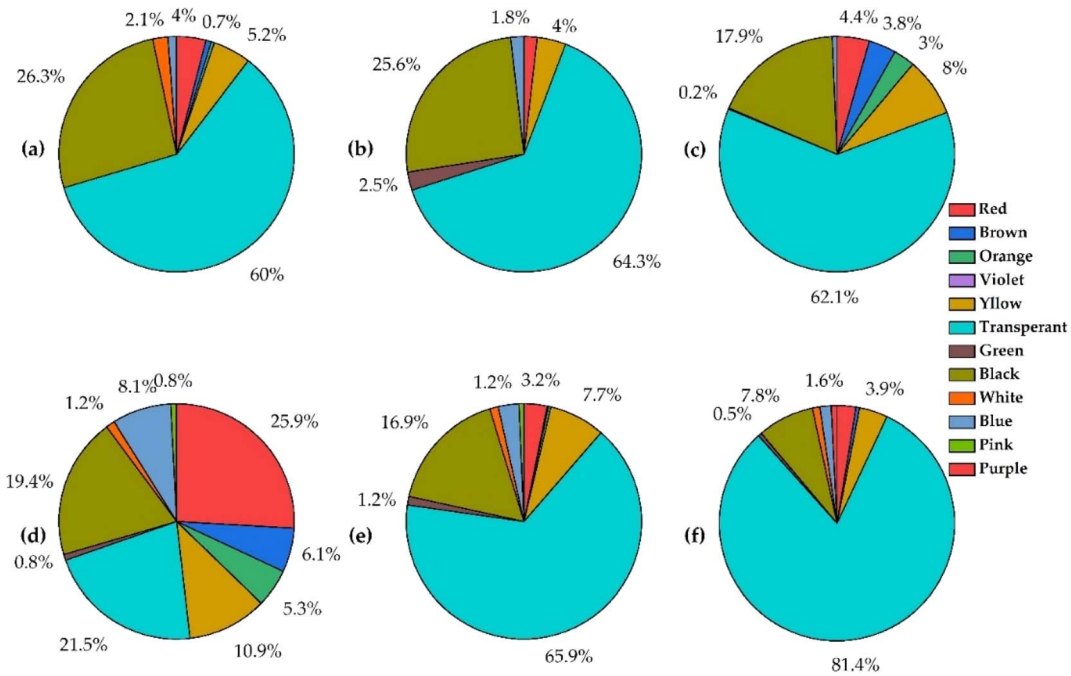

Fig. 6 Color composition of MPs in Shitalakshya River water samples (wet season): (a) SL-1, (b) SL-2, (c) SL-3, (d) SL-4, (e) SL-5, (f) SL-6.

from synthetic textile washing, plastic product degradation, and industrial waste.[46]

3.4 Color of MP

The study characterized MPs based on color, revealing a diverse range of hues across samples. Transparent MPs dominated most samples (Fig. 6 and 7), representing the highest proportion (81.39%) in SL-6 water samples (wet season) and the lowest (13.39%) in BL-6 sediment samples (wet season). This transparency primarily results from long-term environmental exposure to UV radiation and physical abrasion against sediments.[47] Black MPs emerged as the second most prevalent color category, while other significant colors included yellow, red, and orange. Notably, yellow MPs showed particularly high abundance in Balu River sediment samples during the wet season, peaking at 42.8% in BL-6 samples – substantially exceeding the transparent MP fraction (13.4%) at the same location. Chemical analysis identified PP and PE as the predominant polymers in transparent and white MPs.[48] Comparative analysis revealed distinct spatial patterns: the Balu River contained higher proportions of green MPs compared to the Shitalakshya River, while the Shitalakshya River maintained consistent dominance of transparent MPs across both seasons and sample types. These color variations reflect the diversity of plastic products in the environment, with more durable-colored plastics representing persistent sources of colored MPs. Wastewater treatment plants were also identified as significant point sources contributing colored MPs to aquatic systems.[49] Comprehensive color characterization provides important insights into MP sources and environmental fate in these river systems.

3.5 Size distribution of MPs

Microplastic size distribution was systematically analyzed across all samples, with particles categorized into three size classes: <0.1 mm, 0.1–0.5 mm, and >0.5–5 mm. Analytical methodologies differed between sample types, with water samples quantifying MPs in the 50 μm to 5 mm range and sediment samples capturing a broader spectrum (1 μm to 5 mm). Comparative analysis revealed the Balu River contained a higher proportion of larger MPs (>0.5 mm) than the Shitalakshya River, particularly evident in wet season sediment samples from BL-6 (4.343% large MPs) and corresponding water samples (3.99% large MPs; Fig. 8c). The Shitalakshya River showed minimal large MPs presence, with only 1.76% detected in SL-3 sediments, and eight sampling points across both rivers completely lacked large MPs.

Smaller MPs (<0.1 mm) consistently dominated the size distribution, representing the majority fraction in most samples. Maximum abundances reached 83.65% in SL-6 water samples (wet season; Fig. 9c) and 83.25% in BL-2 water samples (dry season; Fig. 8a). The lowest proportion of small MPs occurred in SL-4 sediment samples (42.42% during the wet season), demonstrating significant spatial and seasonal variability in size distributions. These findings highlight the prevalence of small microplastics in these river systems while revealing important differences in size class distribution between rivers, seasons, and sample matrices.

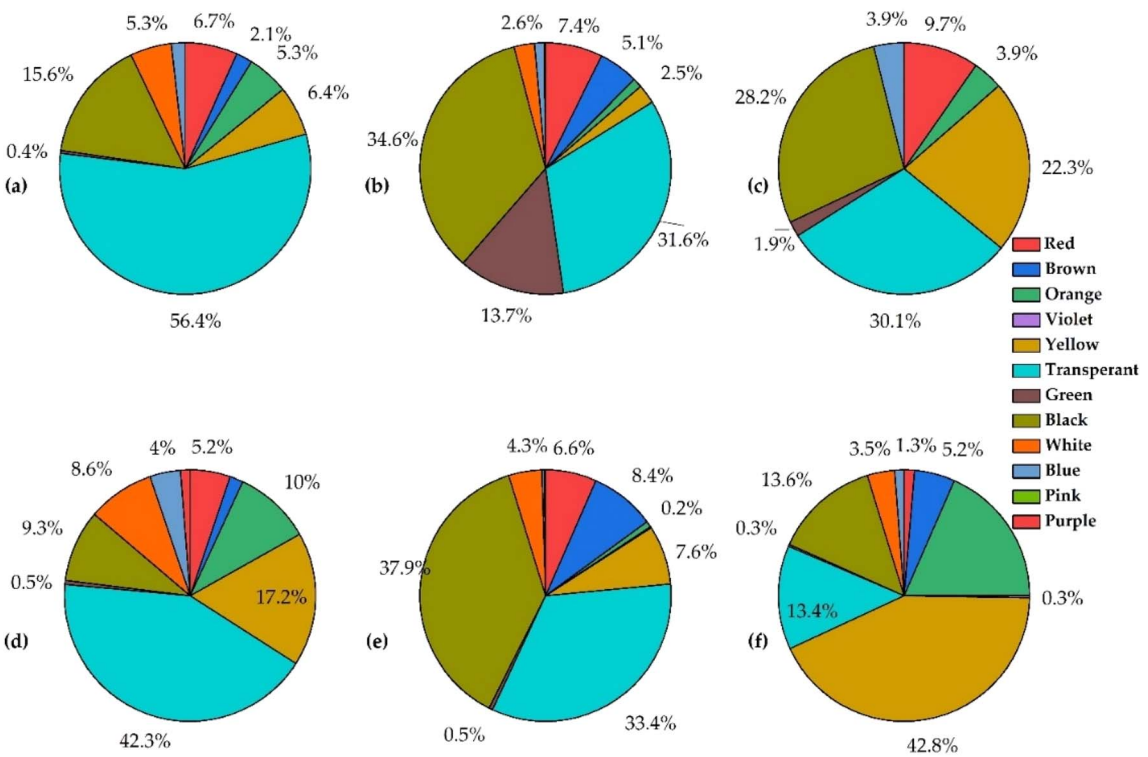

Fig. 7 Color composition of MPs in Balu River sediment samples (wet season): (a) BL-1, (b) BL-2, (c) BL-3, (d) BL-4, (e) BL-5, (f) BL-6.

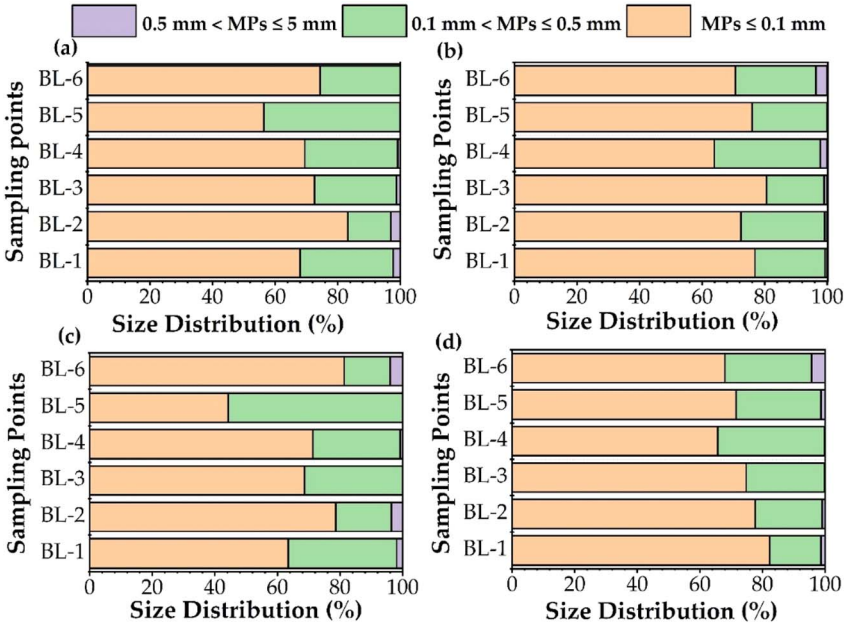

Fig. 8 Size distribution of MPs in Balu River samples: (a) dry season water, (b) dry season sediment, (c) wet season water, (d) wet season sediment.

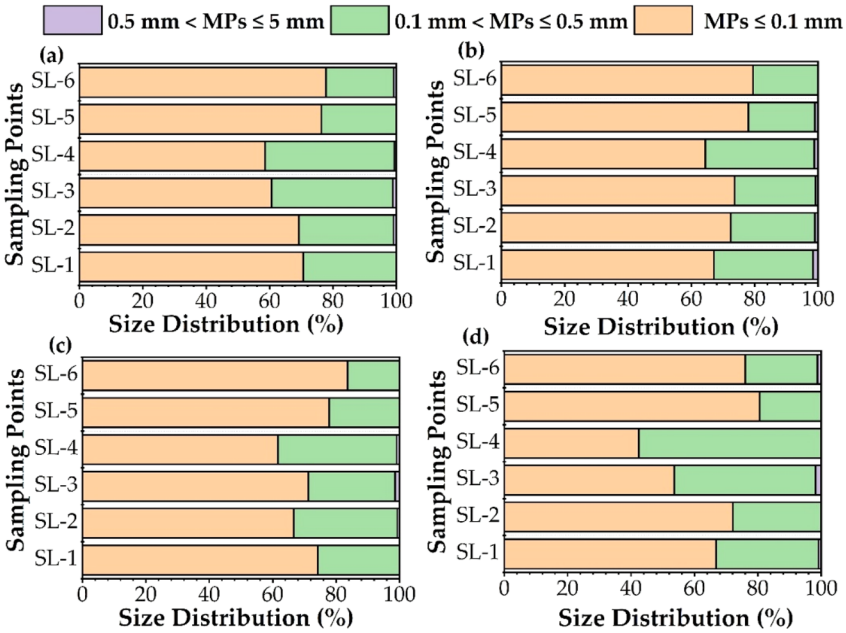

Fig. 9 Size distribution of MPs in Shitalakshya River samples: (a) dry season water, (b) dry season sediment, (c) wet season water, (d) wet season sediment.

3.6 Polymer types of the MPs in water and sediment samples

Fourier-transform infrared (FTIR) spectroscopy analysis confirmed the presence of various types of MPs in both rivers (Fig. S11 to S26). We identified the polymer types based on characteristic absorption peaks observed in the FTIR spectra.

Polyethylene (PE) was found to be the most abundant microplastic polymer detected across nearly all sampling points in both rivers and during both seasons. This prevalence is likely attributed to the widespread use of polyethylene in numerous applications, including packaging materials, containers and bottles, household items, agricultural films, construction materials, medical supplies, and industrial components. In addition to PE, several other polymer types were identified in the samples, including polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and nylon.

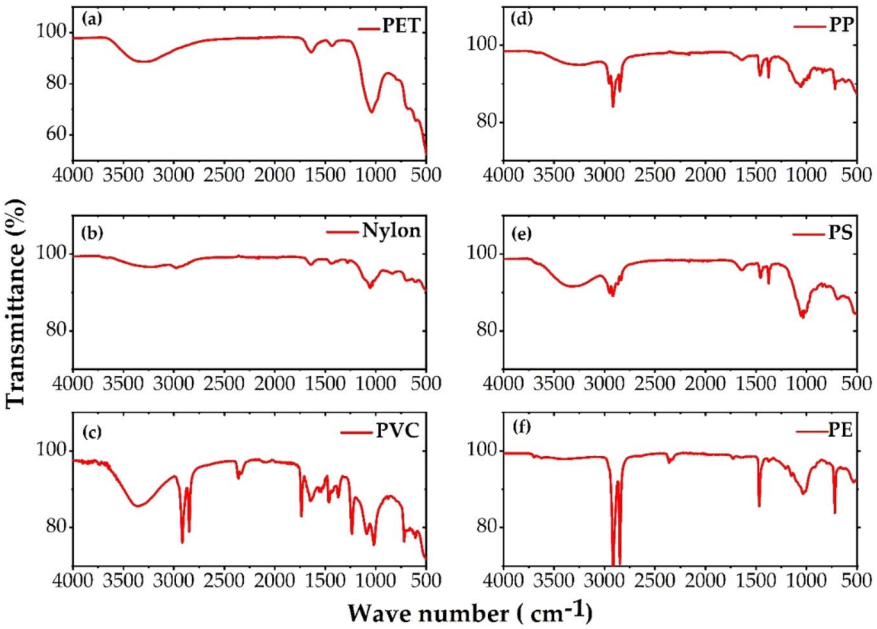

Fig. 10 FTIR spectra of detected microplastics in collected water and sediment samples, (a) PET, (b) nylon, (c) PVC, (d) PP, (e) PS, (f) PE.

FTIR analysis of the microplastic sample shown in Fig. 10a revealed characteristic peaks confirming the presence of PET, at 734 cm^{-1} (aromatic CH out of plane bonding), 1080 cm^{-1} (C–O stretching), 1253 cm^{-1} (C–O stretching), and 1720 cm^{-1} (C=O stretching). These correspond to the presence of PET. Fig. 10b shows peaks confirming the presence of nylon. For nylon, characteristic peaks were observed at 3322 cm^{-1} (N–H stretching, amide A band), 2873 cm^{-1} (aliphatic C–H stretching), 1654 cm^{-1} (C=O stretching, amide I band), 1535 cm^{-1} and 1447 cm^{-1} (CH_2 bending), 1246 cm^{-1} (N–H bending), 680 cm^{-1} (N–H out-of-plane bending). The spectrum in Fig. 10c confirmed the presence of polyvinyl chloride (PVC), as evidenced by a C–Cl stretching vibration at 610 cm^{-1} and 659 cm^{-1}, –CH bending at 1254 cm^{-1}, and CH_2 bending at 1442 cm^{-1}, C–H stretching at 2870 cm^{-1} and 2996 cm^{-1}. These peaks are defining features of PVC.

Polypropylene (PP) was identified in Fig. 10d by characteristic peaks at 2939 cm^{-1} and 2859 cm^{-1} (C–H stretching vibration), 1456 cm^{-1} (CH_2 bending) and 1364 cm^{-1} (CH_3 bending), 1180 cm^{-1} (CH_3 rocking/wagging), 990 cm^{-1} (C–C stretching) and 840 cm^{-1} (CH_2 rocking) are the defining features of PP. Fig. 10e showed distinctive peaks for polystyrene (PS), such as peaks at 2988 cm^{-1}(aromatic C–H stretching), 2850 cm^{-1} (C–H stretching), 1622 cm^{-1} (aromatic C=C stretching), 1420 cm^{-1} (aromatic ring stretching) 1010 cm^{-1} (CH_2 bending), 675 cm^{-1} (aromatic CH out of the plane) are the defining features of PS. Finally, the spectrum in Fig. 10f confirmed PE through peaks at 2918 cm^{-1} (C–H asymmetric stretching), 2820 cm^{-1} (C–H symmetric stretching), 1470 cm^{-1} (CH_2 bending vibration), and 750 cm^{-1} (CH_2 rocking vibration). A comprehensive list of characteristic peaks, their assignments, and corresponding literature references is provided in Table 2. The microplastic types identified from FTIR analysis are summarized in Tables 3 and 4. The results consistently show that PE, PP, and nylon were the most frequently identified microplastic types in the samples analyzed. A comprehensive

Table 2 FTIR characteristic peaks of different polymers

Polymer type	Characteristic peaks	Ref.
Polystyrene (PS)	3050 (aromatic C–H stretching), 2840 (C–H stretching), 1601, 1440 (aromatic ring stretching), 1022 (CH_2 band), 670, and 530 cm^{-1} (aromatic CH out-of-plane bending)	27, 42 and 43
Nylon	3290 cm^{-1} (N–H stretching), 2932 and 2858 cm^{-1} (C–H stretching), 1662 cm^{-1} (C=O stretching), 1533 and 1464 cm^{-1} (CH_2 band), 1284 (N–H band), 687 cm^{-1} (N–H out-of-plane bending)	31 and 53
PET	1713 cm^{-1} (C=O stretching), 1260 cm^{-1} (C–O stretching), 1096 cm−1 (C–O stretching), 720 cm^{-1} (aromatic CH out-of-plane bending)	31, 52 and 53
PP	2922 cm 2854 cm^{-1} (C–H stretching vibration) 1456 (CH_2 bending) and 1375 cm (CH_3 bending) 1166 cm^{-1} (CH_3 rocking), 981 cm^{-1} (C–C stretching) and 847 cm^{-1} (CH_2 rocking)	34 and 54
PVC	2922 and 2854 cm^{-1} (C–H stretching),1427 cm^{-1} (–CH_2 bending), 1250 cm^{-1} (–CH bending) 600 and 650 cm^{-1} (C–Cl gouche bond)	34 and 55
PE	2914 cm^{-1} (C–H asymmetric stretching), 2846 cm^{-1} (C–H symmetric stretching), 1462 cm^{-1} (CH_2 bending vibration), 717 cm^{-1} (CH_2 rocking vibration)	34 and 56

Table 3 The type of polymers obtained from the Balu River

	Dry season		Wet season	
Sampling point	Water samples	Sediment samples	Water samples	Sediment samples
BL-1	Nylon, PE, PP, PVC	Nylon, PP, PVC	Nylon, PE, PVC	PE, PVC
BL-2	Nylon, PE, PP	Nylon, PP, PET	Nylon, PE, PVC	PE, PP, PS, PVC
BL-3	PE, PS, PVC	Nylon, PE, PP, PET, PVC	Nylon, PE, PP, PET, PVC	Nylon, PE, PET, PS
BL-4	PE, PP, PVC	Nylon, PE, PP, PVC	Nylon, PE, PP, PET	Nylon, PE, PP, PET, PVC
BL-5	Nylon, PE, PET, PVC	Nylon, PE, PP, PVC	Nylon, PE, PP, PET, PS	Nylon, PE, PS
BL-6	PE, PVC	PE, PP, PVC	Nylon, PE, PET, PVC	PE, PET, PVC

Table 4 The type of polymers obtained from the Shitalakshya River

	Dry season		Wet season	
Sampling point	Water samples	Sediment samples	Water samples	Sediment samples
SL-1	Nylon	Nylon, PE, PVC	Nylon, PP, PVC	Nylon, PE, PVC
SL-2	Nylon, PE, PET	Nylon, PP, PET, PVC	Nylon, PE, PP, PET, PVC	PE, PVC
SL-3	Nylon, PE, PP, PVC	Nylon, PE, PP, PET	Nylon, PE, PP, PET, PVC	PE, PS, PVC
SL-4	Nylon, PE, PP, PVC	Nylon, PE, PVC	PE, PVC	PE, PP, PET, PS, PVC
SL-5	Nylon, PE, PP, PVC	Nylon, PE, PP, PVC	PE, PS, PVC	PE, PVC
SL-6	Nylon, PE, PP, PET	Nylon, PE	Nylon, PP, PE, PET	Nylon, PE, PVC

listing of all characteristic peaks, their specific vibrational assignments, and corresponding literature references is provided in Table 2. The complete results of microplastic polymer types identified through FTIR analysis are systematically summarized in Table 3 (for the Balu River) and Table 4 (for the Shitalakshya River). The analytical results consistently demonstrate that PE, PP, and nylon were the most frequently identified microplastic polymer types across all samples analyzed from both rivers.

Besides, in this study for separating polymers from water and sediment, NaCl solution was used. But, it is generally considered less hazardous than $ZnCl_2$ or NaI solutions.[50] NaCl (1.2 g cm^{-3}) is insufficient for efficiently recovering denser polymers such as PET and PVC.[51] Therefore, to ensure the recovery of a wider range of polymer types, including these denser polymers, $ZnCl_2$ or NaI solutions are typically recommended for microplastic analysis.

3.7 SEM image analysis

High-resolution scanning electron microscopy (SEM) was conducted to examine the surface morphology of MPs collected from both rivers. The SEM images (Fig. S3–S10, 11 and 12) revealed important characteristics about MP surface degradation and environmental weathering.

Fragment-type MPs showed significant surface damage, including cracks, scratches, and irregular edges (Fig. 11a, c and d). These features suggest mechanical abrasion and chemical weathering processes that may lead to the formation of nanoplastics.[31] The presence of small particles adhered to MP surfaces indicates potential interactions with other environmental contaminants, as supported by previous EDX analysis showing elements like Si, K, Au, C, and O on MP surfaces.[31]

Notable differences were observed between MPs from water and sediment samples. Sediment-derived MPs exhibited much rougher surfaces with more pronounced weathering features (Fig. 11a, c and d) compared to water column MPs (Fig. 11b). This suggests that benthic environments with sediment abrasion and microbial activity accelerate MPs degradation. The irregular surfaces of sediment MPs, particularly the fragment types, indicate extended environmental exposure and weathering over time.

Fiber-type MPs generally showed smoother surfaces than fragments (Fig. 12), though some had attached particles (Fig. 12d) that could represent environmental contaminants or secondary MP fragments. The relative smoothness of fibers may reflect different degradation pathways or shorter environmental residence times compared to fragments.

The SEM analysis provides visual evidence that, (i) MPs undergo significant surface modification in aquatic environments, (ii) sediment exposure causes more severe surface damage than water column exposure, (iii) fragment-type MPs show greater weathering than fiber-type MPs, (iv) MP surfaces can accumulate other particles and contaminants, and (v) environmental conditions influence MP degradation patterns.

Additional SEM images in supplementary materials (Fig. S3–S10) further document these surface characteristics across different sampling locations, seasons, and MP types. The findings demonstrate how SEM imaging can reveal important details about MP aging and environmental interactions that are not detectable by other analytical methods.

3.8 Ecological risk assessment of MPs

The ecological risk assessment of microplastics (MPs) in both rivers was conducted using the Pollution Load Index (PLI), as

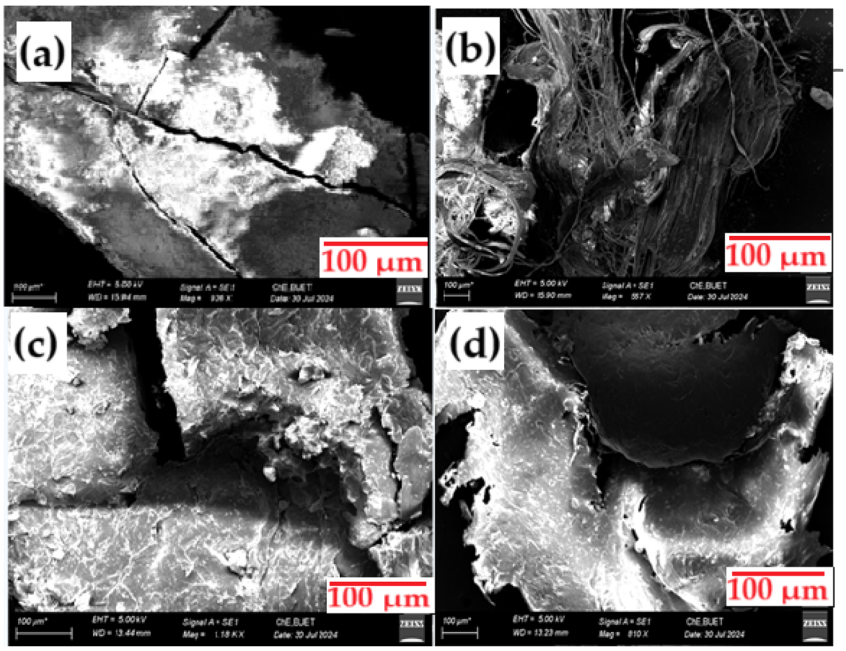

Fig. 11 SEM images of fragment microplastics. (a) BL-4 sediment, (b) SL-2 water, (c) BL-1 sediment and (d) BL-1 sediment in dry season.

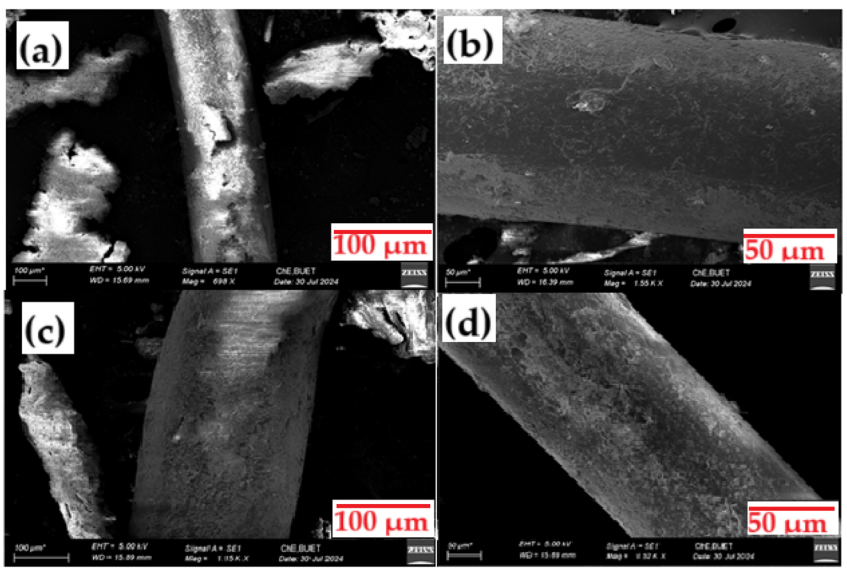

Fig. 12 SEM images of fiber microplastics. (a) BL-4 sediment, (b) SL-2 water, (c) BL-1 sediment and (d) BL-1 sediment in dry season.

detailed in the Materials and methods section. The calculated PLI values showed spatial and seasonal variability, with the highest PLI value (3.19) recorded in sediment samples from the Balu River during the dry season, and the lowest PLI value (1.34) observed in water samples from the Balu River during the wet season. All other PLI values fell within this range. According to established PLI classification schemes,[57] both rivers were categorized as low risk (Level I) and minor hazard,[58] as all values remained below the PLI threshold of 10.

Comparative analysis with regional studies revealed that the PLI values for the Balu and Shitalakshya Rivers were significantly lower than those reported for the Buriganga River (highest PLI = 7.282; lowest PLI = 4.767).[31,37] Similarly, the Turag River exhibited PLI values ranging between 1 and 2,[37] while the Kuakata sea beach recorded an average PLI of 1.2.[59] These comparisons confirm that the MP pollution levels in the studied rivers correspond to a low-risk category relative to other regional aquatic systems.

The observed variability in PLI values within our study highlights the influence of localized pollution sources and seasonal factors on MP distribution. It is important to note that while PLI serves as a valuable indicator of MP pollution levels,[57]

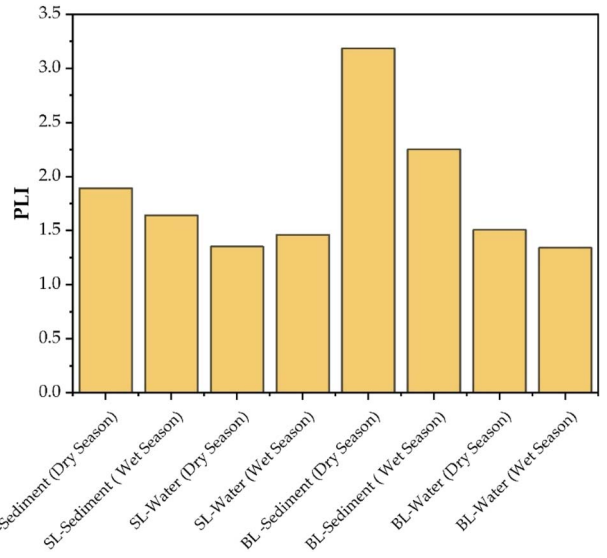

Fig. 13 PLI values of sediment and water samples.

it does not directly measure toxicity or biological impacts. Nevertheless, the PLI assessment provides a standardized framework for evaluating the relative ecological threats posed by MPs in these river systems.

Fig. 13 presents the complete range of PLI values for sediment and water samples, illustrating the spatial and temporal patterns of MP pollution across both rivers. The results underscore the need for continued monitoring to assess long-term trends and potential changes in ecological risk associated with MP contamination in these critical freshwater resources.

However, it is important to note that all PLI values in the experiment are based on regional minima, since true pristine background concentrations are not currently available for Bangladeshi rivers. This methodological limitation may result in an under- or over-estimation of pollution risk levels when compared with studies from other regions that use established references. Future research should prioritize identifying minimally impacted freshwater environments in Bangladesh to serve as reference baselines for more robust PLI calculations.

4 Conclusions and future recommendations

This research provides a comprehensive assessment of microplastic pollution dynamics in the Balu and Shitalakshya Rivers, revealing significant spatial and seasonal variations in MP characteristics. The study demonstrates substantially higher MP concentrations in sediments compared to water columns, with the Balu River exhibiting greater pollution levels than the Shitalakshya, likely due to differing anthropogenic pressures and hydrological factors. The predominance of fragment-type (53.78–95.36%) and transparent MPs, along with the prevalence of <0.1 mm particles, suggests extensive environmental degradation of plastic waste entering these waterways. Polymer analysis identified polyethylene as the dominant constituent (56–82% of MPs), consistent with global patterns of plastic pollution, while polypropylene and polyvinyl chloride represented significant secondary components. Advanced microscopy revealed pronounced surface weathering in sediment-associated MPs, featuring cracks, pits, and erosional features indicative of prolonged environmental exposure. This contrasts with relatively smoother water-column MPs, highlighting compartment-specific degradation processes. While Pollution Load Index values (1.34–3.19) classify both rivers under risk category I, the identified MPs concentrations exceed those of many global freshwater systems, warranting concern. Although the present study did not apply predictive modeling approaches, the findings can serve as a foundation for future applications. The spatial and seasonal patterns identified here may support the development of hotspot prediction tools and seasonal flux estimations of MP loads in river systems. Importantly, these findings underscore the urgent need for integrated waste management policies such as improved urban plastic waste management (including collection, segregation, and recycling), stricter regulation of industrial discharges, investment in and expansion of wastewater treatment infrastructure, and public awareness campaigns to mitigate microplastic pollution in Bangladesh's critical river systems. The data provides a crucial foundation for ongoing monitoring and regulatory efforts to address this emerging environmental challenge, while supporting the development of evidence-based strategies for sustainable river basin management.

The limitations of this study, including size detection constraints and seasonal sampling frequency, suggest directions for future research. The following recommendations have been proposed for future studies on MP analysis:

(i) Stratified sediment sampling to strengthen temporal interpretations of microplastic pollution in riverine systems is also recommended.

(ii) To minimize contamination, all sample handling was carried out inside a clean bench. Only distilled water blanks were included in this study; no additional laboratory procedural blanks, airborne exposure blanks, or spike-recovery tests were performed. Therefore, we recommend that future studies incorporate these controls to enhance the assessment and validation of contamination and recovery.

(iii) Use of Raman spectroscopy for nanoplastic detection, expanded temporal monitoring, and source-apportionment studies would enhance understanding of pollution dynamics. Although we collected both floating and settled solids for analysis of microplastics from the density separation funnel, it is suggested to consider higher density solution for separating heavier MPs that are present in water and sediment samples. For instance, consider higher-density media like $ZnCl_2$ ($\sim$1.6 g cm^{-3}) or NaI ($\sim$3.67 g cm^{-3}) to avoid the loss of heavier MPs like PVC, PET, *etc.*

(iv) Although the present study did not apply predictive modeling approaches, the findings can serve as a foundation for future applications. Therefore, a machine learning approach on microplastics in river water and sediments can be conducted as a future study for predicting hotspots, risks, and seasonal flux

estimation to strict industrial discharge monitoring and plastic waste management for policy implications.

(v) We did not evaluate the role of microplastic color in detection or ecological impacts. Since color may influence polymer degradation, visibility, and the likelihood of ingestion by aquatic organisms, we acknowledge this as a limitation and emphasize that future research should address this parameter in greater detail.

Author contributions

Conceptualization, H. R. and M. S. I.; methodology, H. R., R. A., M. S. I., and M. M. R.; validation, R. A., M. S. I. and M. M. R; formal analysis, V. K. R., and M. N. T.; investigation, V. K. R., M. N. T., and H. R.; data curation, V. K. R., M. N. T., and H. R.; writing—original draft preparation, V. K. R., M. N. T., and H. R.; writing—review and editing, V. K. R., M. N. T., H. R., R. A., M. S. I., and M. M. R.; supervision, R. A., M. S. I., and M. M. R.; project administration, R. A., M. S. I., and M. M. R.; funding acquisition, R. A., and M. M. R.; all authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Authors have no known conflict of interest.

Data availability

The raw FTIR spectral data (.csv files) supporting this study have been deposited in the open-access repository Zenodo and are publicly available at: **https://doi.org/10.5281/zenodo.17237954**. The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: **https://doi.org/10.1039/d5ra05599g**.

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