WOODPECKER

THE DROWNED WORLD

Climate, Gender and Marginality in the Sundarbans

Edited by

DR. JAGANNATH MAHATO
PRALOY KUMAR HALDER
RAKESH SASMAL

SAGAR ISLAND'S MICROPLASTIC BURDEN: A DROWNED WORLD'S NEWEST THREAT

Animesh Tiwari[1] and Nairit Panday[2]

1. *Student, Kalinga Institute of Industrial Technology, Bhubaneswar, Odisha*
2. *Student, Kalinga Institute of Industrial Technology, Bhubaneswar, Odisha*

Estuarine and Coastal Studies Foundation

ABSTRACT

Plastics are synthetic materials made from polymers that degrade slowly, causing pollution and breaking into tiny microplastics (MP). Sagar Island, in India's Sundarbans Ramsar site, faces threats from MP from human sources. We measured MP in seawater and sediment, finding mostly fibrous shapes and blue or black colours. FESEM-EDX showed surface damage and trapped pollutants. Spectroscopy identified four polymers: PVC, PE, PET, and PS. This study provides new data on MP levels in the area.

Keywords: *Plastic pollution, Microplastics, Ramsar site, Anthropogenic sources, Surface degradation, Raman spectroscopy.*

1. INTRODUCTION

1.1. Plastic Pollution

Plastic pollution has emerged as a critical environmental challenge in recent times. Because of improper management and disposal practices, a large amount of plastic waste enters the environment through various pathways and causes serious environmental pollution problems (Jambeck *et al.*, 2015; Geyer *et al.*, 2017). It was estimated that 60-99 million tons of plastics were inappropriately disposed of in the environment worldwide in 2015 (Lebreton and Andrady 2019). In 2024, the world is predicted to produce 220 million tons of plastic waste, which exceeds the world's waste management capacity.

1.2. Plastic Accumulation in Sea and Soil

The accumulation of solid plastics in various ecosystems, particularly oceans, rivers, and soil, poses threats to wildlife and human health.

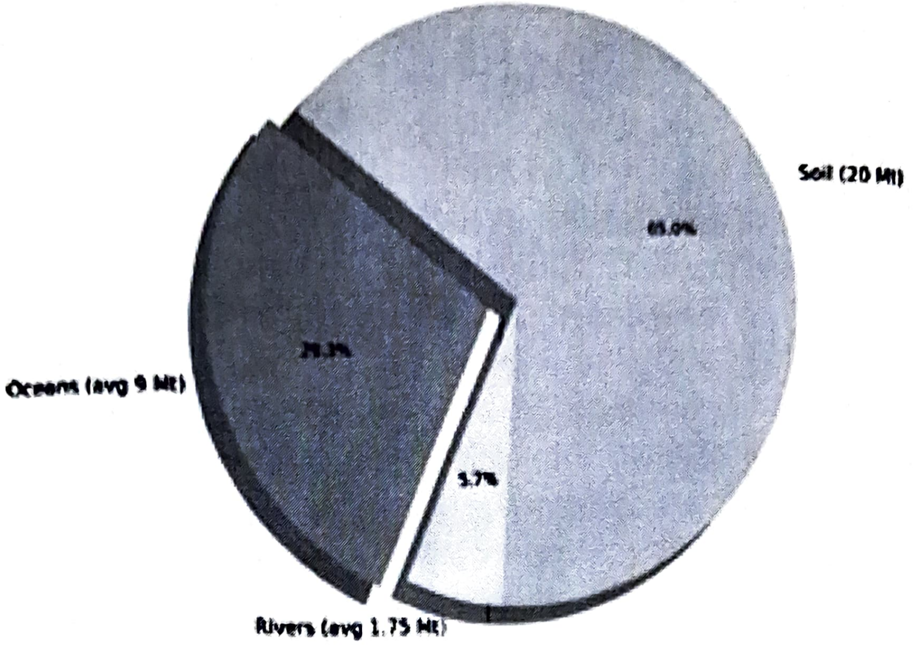

Fig. 1: *Estimated annual plastic waste distribution in 2022.*

Plastics may be transported from land to water primarily by precipitation, surface runoff, and riverine transport (van Emmerik *et al.*, 2019; Rech *et al.*, 2014). Fava (2022) reported that plastics contaminate the marine environment at an extent of 80% of total marine pollution. The annual discharge of plastic waste in the ocean is approximately 8-10 million metric tonnes. The correlation between hydrological factors and plastic mobilization is also notable, as flood events can significantly enhance the transport of plastic into aquatic systems. Regions that are prone to flooding often coincide with high potential for plastic pollution, indicating a need for integrated flood risk management and plastic pollution mitigation strategies (Klein *et al.*, 2021).

Research on riverine systems reveals that urbanization, stormwater runoff, and direct deposition by individuals are significant contributors to coastal litter (Mai *et al.*, 2019). By 2060, mismanaged plastic waste (MPW) will be a serious problem, especially for developing nations in Asia and Africa, which are predicted to be disproportionately affected by future plastic buildup (Lebreton & Andrady, 2019).

While much of the focus has been on marine environments, the accumulation of solid plastics in soil and terrestrial ecosystems has also been documented. The implications of plastic waste disposal on public and environmental health are profound, with studies linking plastic waste to various ecological and health issues (Alabi Okunola *et al.*, 2019). The contamination of freshwater ecosystems with plastic debris further highlights the pervasive nature of plastic pollution, impacting not only aquatic life but also terrestrial ecosystems through runoff and deposition (Dris *et al.*, 2015).

1.3. Plastic to Microplastic Conversion

Physical, chemical, and biological processes can cause plastic waste to gradually decompose and produce a variety of smaller plastic debris (Plastics Europe 2019). According to Galloway and Lewis (2016), the particles were dubbed "microplastics," and microplastic contamination emerged as a global concern. Generally, microplastics, the emerging contaminants, with a diameter of <5mm (Zhang *et al.*, 2025) are obtained from plastics, which are made artificially from oil and gas monomers (Cole *et al.*, 2011). These microcontaminants are classified as primary (Wang *et.al.*, 2021) microplastics originate from cleaning goods, such as facial cleansers, toothpastes, and shower gels and secondary microplastics, which are degraded from bulk plastics (Auta *et. al.*, 2017; Gewert *et. al.*, 2015). Microplastics from real environments are more diverse and complex in types, shapes, sizes, and compositions, which are believed to be related to their toxicity (Lambert *et al.*, 2017).

Plastics' chemical stability and slow breakdown cause them to accumulate in marine environments. Upon entering marine habitats, microplastics aggregate in offshore regions or are redistributed into the

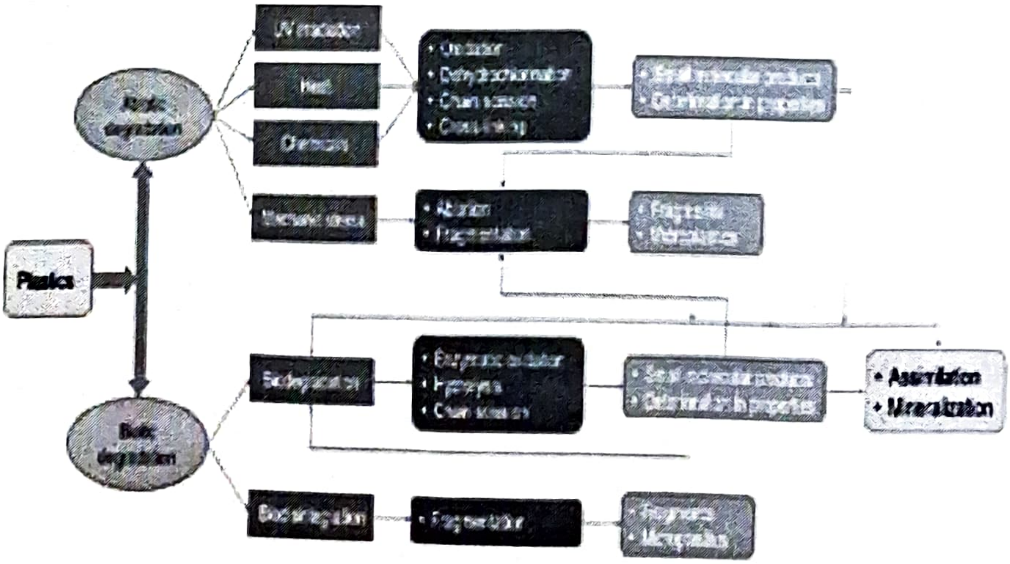

Fig. 2: *A schematic diagram showing the general processes involved in the degradation of plastics.*

sea by winds and ocean currents. Numerous physical mechanisms, including open ocean processes, Stokes drift, internal tides, wind force, Langmuir circulation, ice formation, melting, and drift, among others, control the movement of floating plastic waste in aquatic environments (van Sebille *et al.*, 2020). MP are highly abundant in marine environments, especially along the coastline. Polymers with a range of sizes from less than 50 µm to more than 1600 µm and different morphologies (spheres, fibers, pieces, etc.) have been identified, including polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) (de Sa *et al.*, 2018).

1.4. Microplastics (MP) Pollution in Sundarbans: A UNESCO World Heritage Site

Sundarban is the world's largest delta, enriched with a vibrant mangrove forest that supports a diverse fauna and flora. This delta is formed by convergence of Ganga, Bhamhaputra and Meghna River, meeting at the northern Bay of Bengal. Sundarban and the Bay of Bengal receive nearly 4 million tonnes of MP annually from rivers in India and Bangladesh (Kumar *et al.*, 2022). Chatterjee *et al.* (2024) reported accumulation of heteromorphic MP in water, sediment and two species of resident goby fishes of Sundarban of India. According to Sunitha *et al.* (2021), industrial discharge, wastewater effluent, local fisheries, agriculture, and tourism account for the majority of MP in the Bay of Bengal. Furthermore, cyclonic events that involve heavy precipitation contribute a considerable amount of plastic particles to the Bay of Bengal and bring a large amount of plastic debris into the Sundarbans (Kumar *et al.*, 2022). Sagar Island, located within the Sundarbans, faces potential threats from micro-plastic pollution, which could affect both the local

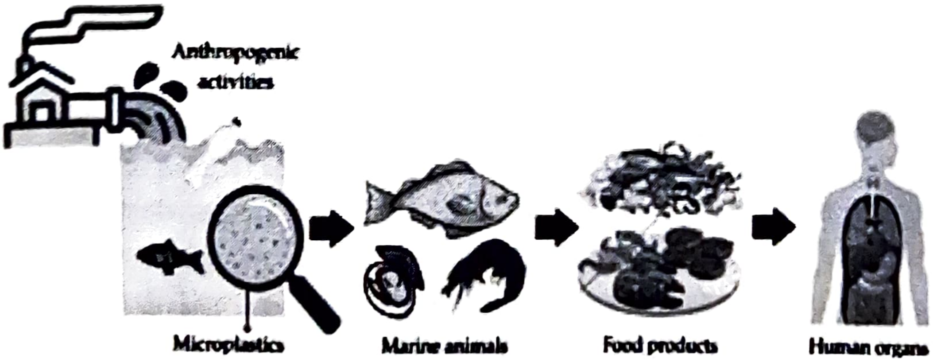

Fig. 3: *Microplastics accumulation in marine animals and humans due to anthropogenic pressure.*

biodiversity and human health. Recent studies indicate that micro-plastics are present in various environmental compartments, including water and sediments, highlighting the need for localized assessments in Sagar Island (Sahana *et al.*, 2019). In the context of Sagar Island, where local communities rely on aquatic resources, understanding the implications of micro-plastic pollution on human health becomes essential (Blackburn and Green, 2021).

1.5. Microplastics (MP) pollution in Gangasagar Island

Sagar Island, located at the confluence of the Ganges and the Bay of Bengal, is increasingly experiencing micro-plastic pollution as a result of various anthropogenic pressures. The most significant contributor is the Gangasagar Mela, a large-scale annual pilgrimage that attracts millions of visitors and generates substantial quantities of plastic waste, including single-use items such as bags, bottles, and packaging materials. Although waste management efforts are implemented during the event, a considerable portion of plastic debris remains uncollected or improperly disposed of, leading to fragmentation and the formation of micro-plastics in terrestrial and aquatic environments. Additionally, the expansion of tourism and urban settlements on the island has increased the consumption of plastic products, further straining the limited waste management infrastructure. The local fishing industry also contributes to micro-plastic contamination through the disposal and degradation of synthetic fishing gear and ropes. These micro-plastics are increasingly detected in coastal sediments and marine organisms, posing serious ecological risks and potential health hazards through bio-accumulation. Addressing this issue requires integrated waste management strategies, public awareness campaigns, and the enforcement of stricter regulatory frameworks to mitigate plastic leakage into the environment.

2. MATERIALS AND METHODS

2.1. Site Selection

Sundarbans Biosphere Reserve is a Ramsar site and largest mangrove forest (Basu *et al.*, 2021). Sagar island, a popular tourism destination, is situated on the continental shelf of Bay of Bengal (Sharma *et al.*, 2014). This island is recognized as the most densely populated (Hajra *et al.*, 2012) and the largest island of Indian Sundarbans (Sarkar *et al.*, 2021). The increasing pressure of urbanization is making this site vulnerable. According to Sharma *et al.* (2014), the second-largest assemblage of

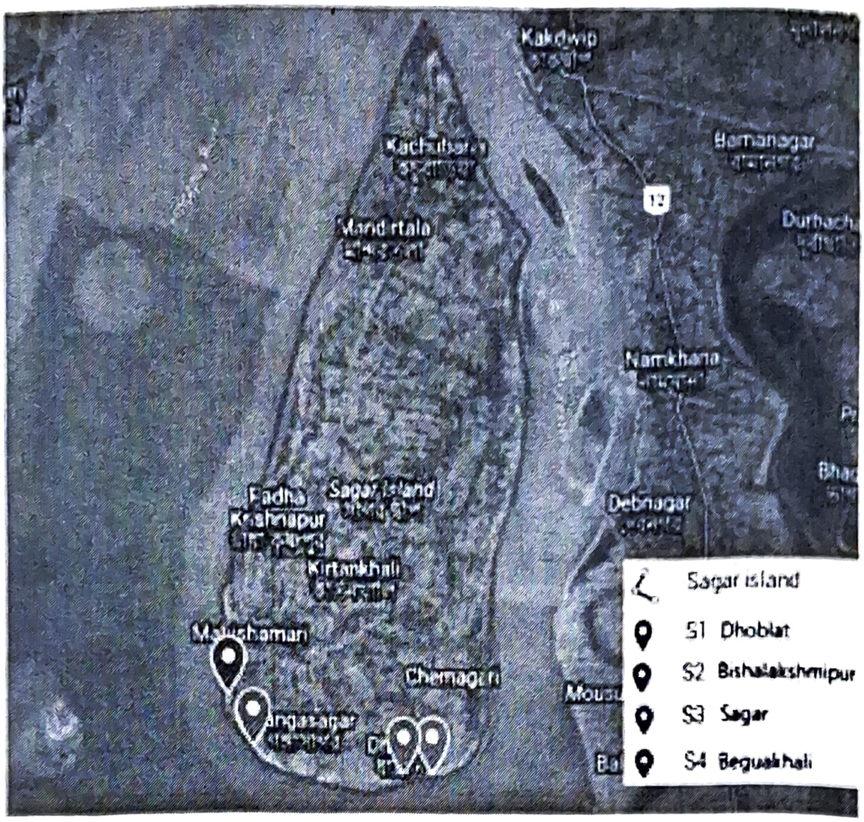

Fig. 4: *Different sampling sites of Sagar Island for microplastics isolation.*

human devotees in India is the Ganga Sagar religious fair on Sagar Island. Apart from tourism, this site is impacted environmentally with ferry movement, domestic sewage disposal and fishing activity. My site selection to collect the samples were Dhoblat (site S1: 21°37′ 21″N 88°2′ 17″E), Bishalakshmipur (site S2: 21°50′ 6″N 88°14′ 5″E), Sagar beach (site S3: 21°39′ 10″N 88°04’31″E) and Lighthouse/Beguakhali (site S4: 22°39′ 37″N 88°15′ 41″E) are located along the coastline of Northern Bay of Bengal. These sites were selected based on differential anthropogenic pressure and availability of the experimental specimens.

2.2. Collection of Sea Water and Sand

Sea water was collected from four experimental sites with three replicates from each site. A volume of 2L of sea surface water (from the depth of 1-10 cm) was collected to avoid sand or sediment particles (Zhang *et al.*, 2020). Sand samples were collected from the beach during low tide from an area of 0.5 m^2 up to a depth of 5 cm from surface (Tiwari *et al.*, 2019) with three replicates. Approximately 1 kg of sand samples were collected in a glass container for each replicate of three sites and transported to the laboratory.

2.3. Isolation of MP from Water and Sand

200 ml of sea water with filtered residues was taken in a glass beaker and it was treated with 10 ml of 30% H_2O_2 to degrade the organic matter present, the beaker was kept undisturbed for a minimum of 8 hours or until no foam was observed (Wang *et al.*, 2021). The digest was filtered using a glass microfiber filter (Himedia; GF/A: 24 mm, 1.2 µm), the filter paper was allowed to dry at room temperature and kept in a covered petri plate for further identification.

The bulk soil samples were dried in a hot air oven at 60°C for 48 hours. For the sample analysis, 1 kg of dry beach sediment was sieved with 5, 4, 3.3, 2, and 1 mm sieves. Transfer the particles retained on 4, 3.3, 2 sieve and 100 g of sieved sand samples from 1 mm sieve were collected and transferred to a glass beaker. Micro-plastics were isolated by the density separation method as reported by Lots et al. (2017) and Patchaiyappan *et al.* (2020). The same method with slight modification was adopted in this work to enhance the yield of micro-plastics (Yaranal *et al.*, 2021). 360 g NaCl (HiMedia Laboratories Pvt. Ltd., Mumbai, India) was dissolved in 1 L distilled water to prepare a supersaturated NaCl solution (density 1.2 g/cm³). An aliquot of 50 g air dried sediments from each site was weighted in a glass beaker and mixed with 200 ml of supersaturated sodium chloride solution (1.2 g/L) in a 250 ml conical flask. Stir the conical flask at 900 rpm for 2 minutes and leave it undisturbed for a minimum of 8 hours. After 8 hours 75-100 ml of the supernatant was poured and filtered using glass microfiber filter (Himedia; GF/A: 24 mm, 1.2 µm) and the membrane was dried and kept in a covered glass petri plate.

2.4. IDENTIFICATION, PHYSICAL AND MORPHOLOGICAL CHARACTERIZATION OF MP

2.4.1. Bright Field Compound Microscope

The dried filter paper was observed under a compound microscope first at 10X magnification and then under 40X magnification. The shape, size, and color of micro-plastics were visually estimated in order to categorize them based on their physical attributes. In both bright and dark field imaging, it was challenging to differentiate between transparent and white micro-plastics.

2.4.2. Fluorescence Microscope

20 µg ml^{-1} Nile Red (CAS Number: 7385-67-3, SRL) was used to stain dried environmental samples, which were then incubated for 10 minutes at 50°C (Konde *et al.*, 2020). Using fluorescent microscopy (Olympus BX53) with excitation and emission wavelengths of 550 nm and 580 nm, respectively, post-stained MP were analyzed. To examine, count, and characterize the size, shape, and color of the environmental MP, photo documentation of fluorescent particles was done at a magnification of 4×.

2.4.3. FESEM- EDX

For FESEM analysis the sample was first fixed with carbon tape followed by coating with a thin layer of gold and palladium, since MP samples are non conductive and coating of the samples are necessary to prevent destruction due to heat.

2.5. CHEMICAL CHARACTERIZATION OF MP

2.5.1. ATR-FTIR

Using Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR), the polymer composition of the isolated MP was determined. This spectrometer (Bruker ALPHA Platinum ATR-FTIR) has a pressure applicator and a diamond module with a single reflector ATR. The analyses were conducted in the mid-IR range of 400-4000 cm^{-1} using a single beam reflection mode, with 32 scans per MP particle. Acetone was used to clean the ATR crystal before each sample was analyzed. To identify certain MP polymers, the resulting spectra were compared to the reference spectra of Miloloza *et al.* (2021).

2.5.2. Micro Raman Spectroscopy

Raman Spectra of the MP samples were recorded within a range of 400-3200 cm^{-1} using a confocal micro-Raman spectrometer (RENISHAW InVia Raman Microscope). All the Raman Spectroscopic measures were done in room temperature with a solid-state laser of excitation wavelength of 532 nm and 785 nm in back scattering configuration.

3. RESULTS

Table 1: *Parameter of soil and Water collected from different sampling sites.*

Area	Water Parameter			Soil Parameter	
	pH	TDS (ppt)	Temp. (°C)	EC (mS/cm)	Temp. (ppt)
Dhoblat 1	6.20	7.60	21.30	3.82	27.0
Dhoblat 2	6.18	16.15	23.16	3.87	27.6
Dhoblat 3	6.15	17.68	23.88	3.24	27.2
Bishalakshmipur 1	6.19	16.62	23.53	3.37	27.7
Bishalakshmipur 2	6.22	18.33	23.30	3.38	28.6
Bishalakshmipur 3	6.25	18.75	23.15	3.40	29.0
Sagar 1	6.31	19.20	23.02	2.86	26.9
Sagar 2	6.25	17.90	22.71	3.87	26.9
Sagar 3	6.35	26.45	23.24	3.63	25.4
Beguakhali 1	6.32	20.30	23.02	4.00	26.9
Beguakhali 2	6.30	20.34	23.76	3.93	27.4
Beguakhali 3	6.27	21.60	23.87	3.85	27.8

The above table shows the water parameter and soil parameter respectively from the 4 sampling sites with three replicates each. For the water parameter we measured the pH, TDS and temperature. For the soil sample we measured the temperature and the electrical conductivity of the soil. The lowest mean pH of all the three replicates from each site was observed in Dhoblat and the highest mean pH of all the three replicates from each site was observed in Sagar beach followed by Beguakhali. The average pH of all the sites was observed to be 6.24.

The highest mean temperature was observed in Beguakhali and the lowest mean temperature was observed in Dhoblat. The mean temperature of all the sites was observed to be 23.16°C.

In the soil the highest mean EC was observed in Beguakhali and the lowest EC was observed in Bishalakshmipur. The average EC of all the sites was found to be 3.60 (mS/cm). The highest mean temperature in soil was observed in Bishalakshmipur and the lowest mean temperature was observed in Sagar beach, the mean temperature of soil from all the sites was found to be 27.37°C.

3.1. Physical Characterization of MP

3.1.1. *Color and Shape of Microplastics*

The colour of MPs can serve as an indicator of their origin, including packaging, laundry industry and fishing gears (Wicaksono *et al.*, 2021). Transparent plastics are commonly used as food container, packaging material and also as transparent fishing line, whereas blue MP's mostly originate from degradation of plastic straws, fishing and aquaculture gears. Commercial laundry activity, wastewater treatment plant, sewage waste water, fishing gears and fishing lines have been identified as major sources of fibrous MP's in estuarine water (Gago *et al.*, 2018). According to Sarkar *et al.* (2019), municipal effluent from washing garments might be the potential sources of MP fibers in River Ganges. Higher abundance of MP fibers were recorded in the surface water of Ganga River (Napper *et al.*, 2021). MP fragments originated from degradation of plastic wrappers and commercial bags. Our study recorded fibrous micro-plastic as the most dominant followed by fragments. Fibrous micro-plastics were more prevalent in the water samples whereas fragment micro-plastics were more prevalent in the sediment samples. Prevalence of the fibrous MP could be linked to weathering of geotextiles and improper disposal of household textiles (de Oliveira *et al.*, 2023).

The coloration of MP often reflects their sources (Saad *et al.*, 2022), moreover, they potentially contain toxic colorants that pose risks to aquatic organisms. We identified five different coloured MP (Fig. 5), including transparent, white, red, blue, black from four different experimental sites of the Sagar Island. In our study black and blue micro-plastics were the most prevalent, blue and black micro-plastics are often linked to specific sources like fishing gear and general plastic debris.

3.1.2. *Surface Topology and Elemental Characteristics of MP*

Electron microscope observations of the isolated MP's from seawater and sediment revealed the characteristics of their surface texture (Fig. 6). Structural deformities and abrasion suggested mechanical tearing or environmental actions producing fragility and disintegration of MP particles. According to Sanchez-Hernandez *et al.* (2021), cracks on the MP surface indicate gradual weathering and oxidation brought on by continuous wave action, changes in salinity, and solar exposure. The oxidative damage caused by temperature fluctuations in sediments is reflected on the porous surface of MP's. Previous reports in Sundarbans mangrove environment confirmed the presence of trace elements in

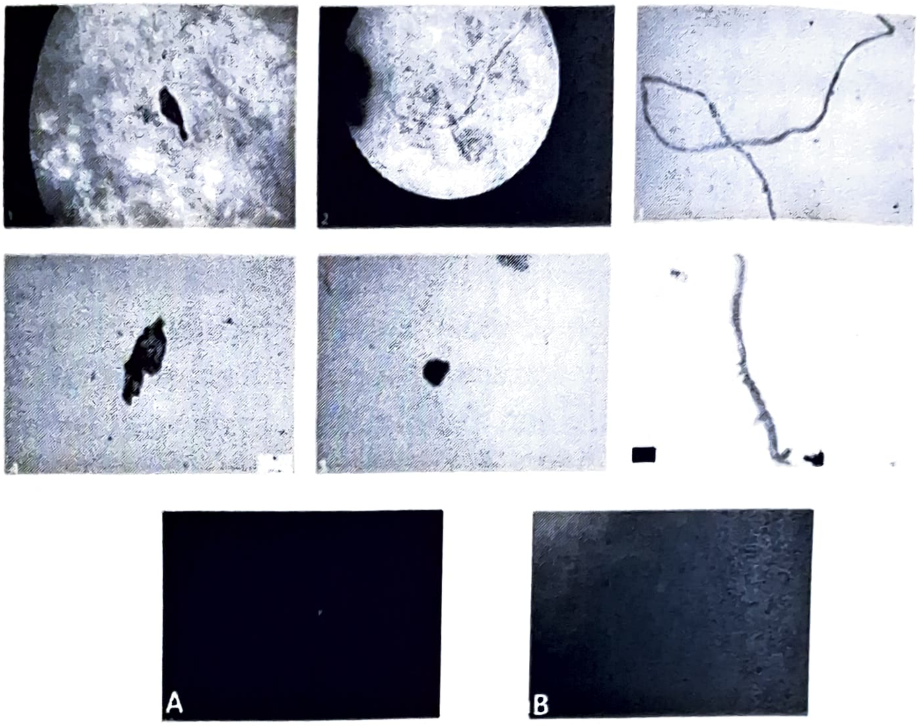

Fig. 5: *Bright field images of MP collected from sea water (1-3) and sand (4-6) Fluorescence microscopic images of MP isolated from sea water (A) and sand (B).*

water and sediment (Kumar *et al.*, 2019). Understanding the surface properties of MP particles with elemental composition is possible by FESEM-EDX investigations. After the EDX analysis of the MP surface we found the presence of Na, Mg, Al, Si, Ca, Zn and other elements like C, N, P, O, Cl, Si in the MP samples isolated from water and sediment. Adsorption of metal from surrounding environments is aided by the high surface imperfections of old MP's, which include many pores, cracks, avulsions, fractures, pits, and roughness.

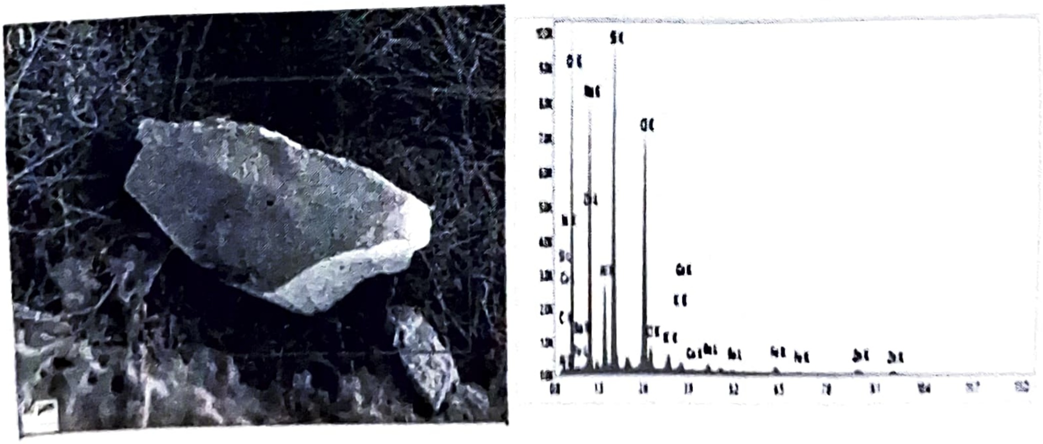

Fig. 6(A): *FESEM images of MP's isolated from water along with their Energy-dispersive X-ray spectra showing surface elemental composition.*

Table 2: *Percentage of elements found on the surface of MP's in water.*

Element	Weight %	Atomic %	Net Int.	Error %	R %	A	F
C K	10.5	17.1	53.8	14.9	0.8981	0.0358	1.0000
N K	2.1	2.9	33.3	17.9	0.9042	0.0585	1.0000
O K	40.7	49.6	1830.0	10.1	0.9092	0.1234	1.0000
Na K	13.4	11.4	1418.3	8.9	0.9219	0.2710	1.0035
Al K	3.5	2.5	665.1	7.5	0.9295	0.4540	1.0097
Si K	11.5	8.0	2559.9	5.9	0.9329	0.5557	1.0080
Cl K	11.8	6.5	2233.7	3.9	0.9423	0.7626	1.0104
K K	1.1	0.6	177.1	7.3	0.9480	0.8188	1.0181
Ca K	0.7	0.3	90.4	11.3	0.9507	0.8585	1.0223
Fe K	1.1	0.4	84.3	10.0	0.9657	0.9666	1.0751
Zn K	1.5	0.5	61.1	9.8	0.9754	0.9866	1.1352
Ba L	2.1	0.3	94.7	15.0	0.9584	0.9241	1.0097

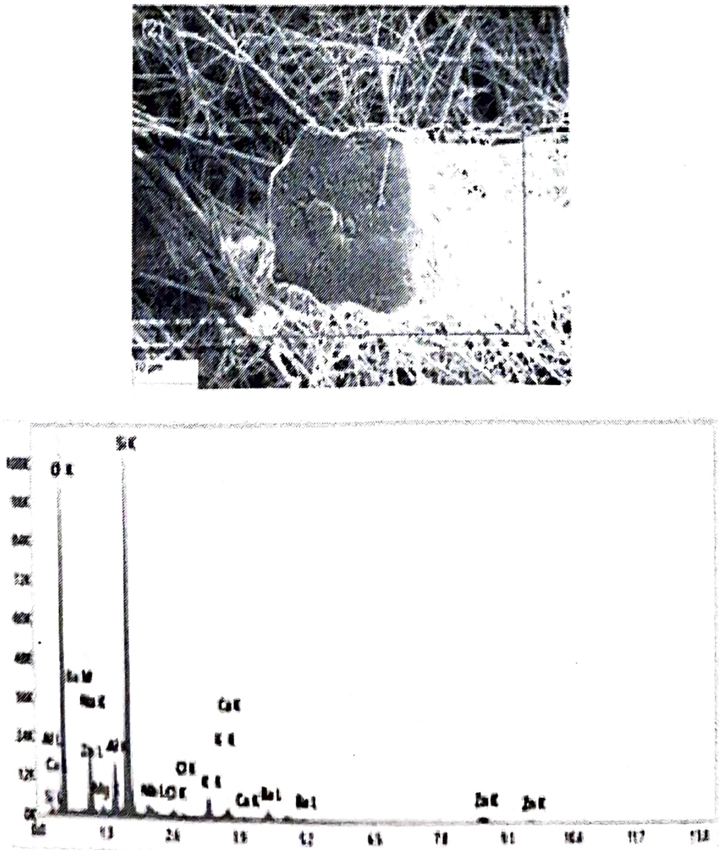

Fig. 6(B): *FESEM images of MP's isolated from sand along with their Energy-dispersive X-ray spectra showing surface elemental composition.*

Table 3: *Percentage of elements found on the surface of MP's in sand.*

Element	Weight %	Atomic %	Net Int.	Error %	R %	A	F
C K	6.8	10.8	56.9	14.7	0.8966	0.0481	1.0000
N K	2.7	3.7	70.0	14.7	0.9029	0.0772	1.0000
O K	54.0	64.4	3650.4	9.7	0.9079	0.1524	1.0000
Na K	4.4	3.6	494.2	9.9	0.9207	0.2391	1.0039
Mg K	0.5	0.4	96.5	11.7	0.9247	0.3349	1.0069
Al K	2.9	2.0	691.3	7.4	0.9284	0.4663	1.0109
Si K	17.0	11.6	4736.5	5.6	0.9319	0.5714	1.0045
Cl K	0.5	0.3	103.0	9.2	0.9413	0.7260	1.0136
K K	1.9	0.9	368.5	5.0	0.9471	0.8444	1.0223
Ca K	1.0	0.5	177.4	7.3	0.9499	0.8750	1.0263
Zn K	2.2	0.6	107.9	7.0	0.9749	0.9877	1.1492
Sr L	2.9	0.6	313.2	7.5	0.9334	0.5649	1.0017
Ba L	3.2	0.4	177.9	9.9	0.9576	0.9318	1.0100

3.2. Chemical Characterization of MP

By analyzing the absorption wavelength of chemical bonds found in MP samples, the isolated MP were described (Fu *et al.*, 2020). The non-destructive, quick, and efficient techniques for determining the types of polymers are FTIR and Raman spectroscopy (Jin *et al.*, 2022). To guarantee the precise chemical characterisation of colored plastic particles, FTIR in conjunction with Raman spectroscopy is required (Kappler *et al.*, 2016). Isolated microplastics were categorized into PE, PVC, PS, PET. FTIR and Raman spectra of isolated MP's are shown in Fig. 7 and 8 respectively.

4. DISCUSSION

From Fig. 4 it can be clearly observed that all the four field sites are on the southern part of Sagar Island. Dhoblat (S1) is a highly vulnerable area due to climate change, particularly erosion and embankment failure. The 2007 cyclone Sidr caused significant damage and devastation in the Bakkhali area within the Shibpur-Dhoblat mouza, impacting settlements and the community (Mukhopadhyay, P. & Dutta, S.C. 2007). Bishalakshmipur is not a prominent part of Sagar Island, research

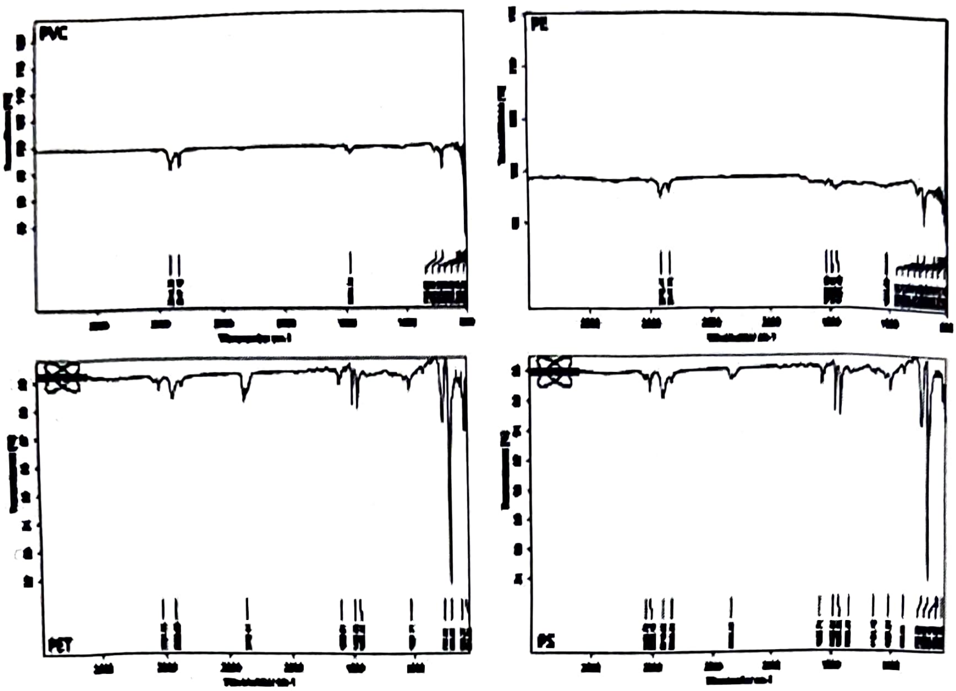

Fig. 7: *FTIR spectra of MP polymers isolated from sea water and sand.*

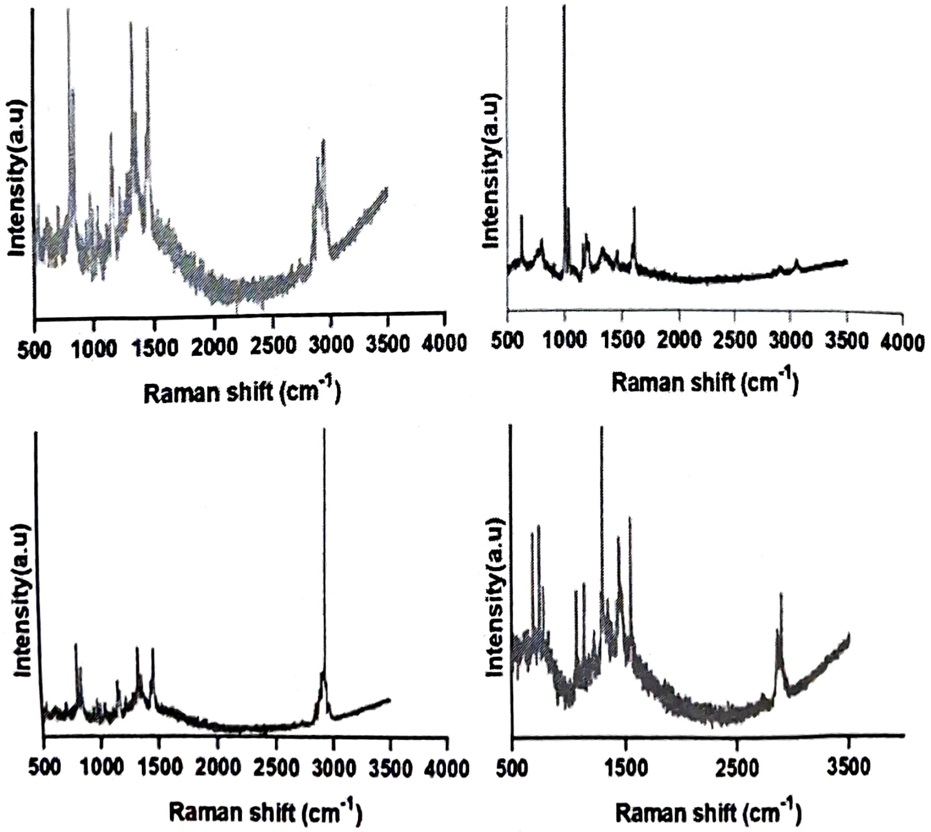

Fig. 8: *Raman Spectra of MP polymers isolated from sea water and sand.*

shows that Bishalakshmipur has the least vulnerability (Narendr. A. *et al.*, 2022). Sagar beach, located in the Gangasagar Island, holds significant environmental importance as a fragile ecosystem highly vulnerable to climate change impacts. The rising sea levels are causing erosion and land loss, impacting the island's unique natural environment and the sacred Hindu pilgrimage site of Gangasagar Mela (https://www.thehindu.com/news/national/west-bengal/a-pilgrimage-meets-climate-change-on-an-island/article69212115.ece). Beguakhali, located on Sagar Island in the Sundarbans, holds ecological significance as a coastal area vulnerable to climate change impacts, including erosion, accretion, and increased cyclonic activity. Its location in the western Sundarbans makes it susceptible to these factors, impacting its vegetation and soil conditions (Paul S. *et al.*, 2024).

Due to a lot of anthropogenic pressure in the Sagar Island, especially from the tourists visiting the island, the plastics and MP's pollution has also been increased. Among all the colours and shape of micro-plastics I isolated from the water and sediment samples, blue and black micro-plastics were more prevalent and fibrous micro-plastics were the most common in all the samples. Blue MP's are often associated with fishing nets whereas black MP's may originate from tires and other rubber products, other colours of MP's like red MP's can be found in fishing gear and textiles while white MP's can be linked to the breakdown of plastic bags and fishing lines. MP's in a coastal environment like Sagar Island can be of various shapes like fragments, fibrous, pellets etc. Fibrous MP's were the most common in the isolated samples. They often arise from synthetic textiles whereas fragment MP's arise from the breakdown of larger plastic items in the environment.

After the chemical analysis of MP's the main categories of MP's were PE, PVC, PS, PET. In coastal environments like the Sagar Island PE enters the water through anthropogenic sources and natural degradation, additionally fishing gear, ropes and nets also contribute to PE pollution. PVC enters the marine environment through agricultural practices and tourism activities. PS pollution in Sagar Island likely includes tourist activities and poor waste management practices. Similarly, PET pollution is high due to tourist activities.

REFERENCES

1. A, Alabi Okunola., I, Ologbonjaye Kehinde., Oluwaseun, A., & E, Alalade Olufiropo. (2019). Public and Environmental Health Effects of Plastic Wastes Disposal: A Review. *Journal of Toxicology and Risk Assessment.* http://doi.org/10.23937/2572-4061.1510021
2. Basu, S., Chanda, A., Gogoi, P., Bhattacharyya, S., 2021. A multi-decadal comparative analysis of a set of physicochemical and nutrient parameters in the tropical tidal creeks of Indian Sundarbans mangrove biosphere reserve. Thalassas: Int. J. Mar. Sci. 37, 303-312. https://doi.org/10.1007/s41208-020-00273-1.
3. Berit Gewert, Merle M. Plassmann and Matthew MacLeod : Environ. Sci.: Processes Impacts, 2015, 17, 1513
4. Blackburn, Kirsty., & Green, D. (2021). The potential effects of micro-plastics on human health: What is known and what is unknown. *Ambio,* 51, 518-530. http://doi.org/10.1007/s13280-021-01589-9
5. Chatterjee, N.H., Manna, S., Ray, A., Das, S., Rana, N., Banerjee, A., Ray, M., Ray, S., 2024. Micro-plastics contamination in two species of gobies and their estuarine habitat of Indian Sundarbans. Mar. Pollut. Bull. 198, 115857 https://doi.org/10.1016/j.marpolbul.2023.115857.
6. Cole, M., Lindeque, P., Halsband, C. and Galloway, T.S. (2011). Micro-plastics as contaminants in the marine environment: a review. *Marine Pollution Bulletin*, 62(12), 2588-2597.
7. de Oliveira, C.R.S., da Silva Junior, A.H., Mulinari, J., Ferreira, A.J.S., da Silva, A., 2023. Fibrous micro-plastics released from textiles: occurrence, fate, and remediation strategies. *J. Contam. Hydrol.* 256 https://doi.org/10.1016/j.jconhyd.2023.104169.
8. Dris, Rachid., Imhof, H., Sánchez, W., Gaspéri, J., Galgani, F., Tassin, B., & Laforsch, C. (2015). Beyond the ocean: Contamination of freshwater ecosystems with (micro-) plastic particles. *Environmental Chemistry*, 12, 32. http://doi.org/10.1071/EN14172
9. Fu, W., Min, J., Jiang, W., Li, Y., Zhang, W., 2020. Separation, characterization and identification of micro-plastics and nanoplastics in the environment. Sci. Total Environ. 721, 137561 https://doi.org/10.1016/j.scitotenv.2020.137561.
10. Galloway, T.S., Lewis, C.N., 2016. Marine micro-plastics spell big problems for future generations. Proc. Natl. Acad. Sci. Unit. States Am. 113 (9), 2331-2333.
11. Gao, S., Yan, K., Liang, B., Shu, R., Wang, N., Zhang, S., 2023. The different ways micro-plastics from the water column and sediment accumulate in fish in Haizhou Bay. Sci. Total Environ. 854, 158575 https://doi.org/10.1016/j.scitotenv.2022.158575.

12. Gago, J., Carretero, O., Filgueiras, A.V., Vinas, L., 2018. Synthetic microfibers in the marine environment: a review on their occurrence in seawater and sediments. *Mar. Pollut. Bull.* 127, 365-376. https://doi.org/10.1016/j.marpolbul.2017.11.070.
13. GESAMP, 2015. Sources, fate and effects of micro-plastics in the marine environment: a global assessment. Retrieved from. https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/GESAMP_microplastics%20full%20study.pdf.
14. Hajra, R., Mitra, R., Ghosh, T., 2012. Impact of gangasagar mela on sustainability of Sagar Island, West Bengal, India. Int. J. Res. Chem. Environ. 2, 140-144.
15. H.S. Auta et al. / Environment International 102 (2017) 165-176.
16. Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A.,Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean.Science 347 (6223), 768e771.
17. Jin, N., Song, Y., Ma, R., Li, J., Li, G., Zhang, D., 2022. Characterization and identification of micro-plastics using Raman spectroscopy coupled with multivariate analysis. Anal. Chim. Acta 1197, 339519. https://doi.org/10.1016/j.aca.2022.339519.
18. Kappler, A., Fischer, D., Oberbeckmann, S., Schernewski, G., Labrenz, M., Eichhorn, K.J.,Voit, B., 2016. Analysis of environmental micro-plastics by vibrational micro-spectroscopy: FTIR, Raman or both ? Anal. Bioanal. Chem. 408, 8377–8391.https://doi.org/10.1007/s00216-016-9956-3.
19. Klein, K., Piana, T., Lauschke, T., Schweyen, P., Dierkes, G., Ternes, T., ... & Oehlmann, J. (2021). Chemicals associated with biodegradable microplastic drive the toxicity to the freshwater oligochaete Lumbriculus variegatus. *Aquatic Toxicology*, *231*, 105723.
20. Konde, S., Ornik, J., Prume, J.A., Taiber, J., Koch, M., 2020. Exploring the potential of photoluminescence spectroscopy in combination with Nile Red staining for microplastic detection. Mar. Pollut. Bull. 159, 111475 https://doi.org/10.1016/j.marpolbul.2020.111475.
21. Kumar, S., Karmoker, J., Pal, B.K., Luo, C., Zhao, M., 2019. Trace metals contamination in different compartments of the Sundarbans mangrove: a review. Mar. Pollut. Bull.148, 47-60. https://doi.org/10.1016/j.marpolbul.2019.07.063.
22. Kumar, R., Sinha, R., Refat Jahan Rakib, M., Padha, S., Ivy, N., Bhattacharya, S., Dhar, A., Sharma, P., 2022. Microplastics pollution load in sundarban delta of Bay of bengal. J. Hazard. Mater. Adv. 7, 100099 https://doi.org/10.1016/j.hazadv.2022.100099.
23. Law, K.L., Thompson, R.C., 2014. Microplastics in the seas. Science 345 (6193),144-145. https://doi.org/10.1126/science.1254065.

24. Lebreton, L., Zwet, J. van der., Damsteeg, Jan-Willem., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, 8. http://doi.org/10.1038/ncomms15611
25. Lebreton, L., Andrady, A., 2019. Future scenarios of global plastic waste generation and disposal. Palgrave Communications 5.
26. Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2017.08.057.
27. Mai, Lei., You, S., He, Hui., Bao, Lian-Jun., Liu, Liang-Ying., & Zeng, E.. (2019). Riverine Microplastic Pollution in the Pearl River Delta, China: Are Modeled Estimates Accurate ?. *Environmental science & technology*. http://doi.org/10.1021/acs.est.9b04838
28. Miloloza, M., Grgic, D.K., Bolanca, T., Ukic, S., Cvetnic, M., Bulatovic, V.O., Dionysiou, D.D., Kusic, H., 2021. Ecotoxicological assessment of micro-plastics in freshwater sources—a review. Water 13, 1-26. https://doi.org/10.3390w13010056.
29. Mukhopadhyay, P. & Dutta, S.C. (2007). A reconnaissance based vulnerability and damage survey report at the Sagar Island, West Bengal: Effect of the Cyclone Sidr of 15th November, 2007. *Bengal Engineering and Science University, Shibpur, India, 22.*
30. Narendr, A., Vinay, S., Aithal, B.H. & Das, S. (2022). Multi-dimensional parametric coastal flood risk assessment at a regional scale using GIS. *Environment, Development and Sustainability*, 24(7), 9569-9597.
31. Napper, I.E., Baroth, A., Barrett, A.C., Bhola, S., Chowdhury, G.W., Davies, B.F.R., Duncan, E.M., Kumar, S., Nelms, S.E., Hasan Niloy, M.N., Nishat, B., Maddalene, T., Thompson, R.C., Koldewey, H., 2021. The abundance and characteristics of micro-plastics in surface water in the transboundary Ganges River. Environ. Pollut.274 https://doi.org/10.1016/j.envpol.2020.116348.
32. Paul, S., Mishra, M., Pati, S., Acharyya, T., Santos, C.A.G., da Silva, R.M. & Laksono, F.A.T. (2024). Evaluation of overwash vulnerability and shoreline dynamics in cyclone-prone Sagar Island, Sundarbans (India). *Science of the Total Environment*, 907, 167933.
33. Plastics Europe, 2019. Plastics The Facts 2019. An Analysis of European LatestPlastics Production, Demand and Waste Data. PlasticsEurope. Available online:https://www.plasticseurope.org/en/resources/publications/1804-plastics-facts2019.
34. Plastics Europe, 2019. Plastics—the Facts 2019. Retrieved from. https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf.

35. Patchaiyappan, A., Dowarah, K., Devipriya, S.P., 2020. Occurrence, distribution and composition of micro-plastics in the sediments of south Andaman beaches. Mar. Pollut. Bull. 156 https://doi.org/10.1016/j.marpolbul.2020.111227.
36. Rech, S., Macaya-Caquilpan, V., Pantoja, J.F., Rivadeneira, M.M., Jofre Madariaga, D., Thiel, M., 2014. Rivers as a source of marine litter—a study from the SE Pacific.Mar. Pollut. Bull. 82 (1-2), 66-75.
37. Saad, D., Chauke, P., Cukrowska, E., Richards, H., Nikiema, J., Chimuka, L., Tutu, H., 2022. First biomonitoring of micro-plastic pollution in the Vaal river using Carp fish (Cyprinus carpio) "as a bio-indicator.". Sci. Total Environ. 836, 155623 https://doi.org/10.1016/j.scitotenv.2022.155623.
38. Sahana, M., Rehman, S., Paul, A., & Sajjad, H. (2019). Assessing socio-economic vulnerability to climate change-induced disasters: evidence from Sundarbans Biosphere Reserve, India. *Geology, Ecology, and Landscapes*, 5, 40-52. http://doi.org/10.1080/24749508.2019.1700670
39. Samarasinghe, K., Pawan Kumar, S., Visvanathan, C., 2021. Evaluation of circular economy potential of plastic waste in Sri Lanka. Environ. Qual. Manag. 31, 99-107.https://doi.org/10.1002/tqem.21732.
40. Sanchez-Hernandez, L.J., Ramírez-Romero, P., Rodríguez-Gonzalez, F., Ramos-Sanchez, V.H., Marquez-Montes, R.A., Romero-Paredes Rubio, H., Sujitha, S.B., Jonathan, M.P., 2021. Seasonal evidence of micro-plastics in environmental matrices of a tourist dominated urban estuary in the Gulf of Mexico, Mexico. Chemo sphere 277.https://doi.org/10.1016/j.chemosphere.2021.130261.
41. Sharma, S.D., Kumar, M., Panda, C.R., Nayak, L., Behera, D.P., Pati, M.P., 2014. Effect of mass bathing on water and sediment quality of Sagar Island beach during Gangasagar mela. J. int. acad. res. multidiscip. 2, 187-199.
42. Sarkar, S., Bardhan, S., Sanyal, P., 2021. LULC change detection studies and its possible linkages with increased visitations in the Sagar Island. W.B. Int. J. Eng. Trends Technol. 69, 49-61. https://doi.org/10.14445/22315381/IJETT-V69I8P207.
43. Sunitha, T.G., Monisha, V., Sivanesan, S., Vasanthy, M., Prabhakaran, M., Omine, K.,Sivasankar, V., Darchen, A., 2021. Micro-plastic pollution along the Bay of Bengal coastal stretch of Tamil nadu, south India. Sci. Total Environ. 756, 144073 https://doi.org/10.1016/j.scitotenv.2020.144073.
44. Sutherland, W.J., Clout, M., Isabelle, M., Daszak, C.P., Depledge, M.H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D.W., De Lurio, J., Impey, A.J., Lickorish, F.,Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L.S., Pretty, J., Prior, S., Redford, K.H., Scharlemann, J.P.W., Spalding, M., Watkinson, A.R., 2010.

45. Tiwari, M., Rathod, T.D., Ajmal, P.Y., Bhangare, R.C., Sahu, S.K., 2019. Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. Mar. Pollut. Bull. 140, 262-273. https://doi.org/10.1016/j.marpolbul.2019.01.055.

46. van Emmerik, T., Strady, E., Kieu-Le, T.C., Nguyen, L., Gratiot, N., 2019. Seasonality of riverine macroplastic transport. Sci. Rep. 9.

47. van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A.,Bergmann, M., Chapron, B., Chubarenko, I., Cozar, A., Delandmeter, P., Egger, M.,Fox-Kemper, B., Garaba, S.P., Goddijn-Murphy, L., Hardesty, B.D., Hoffman, M.J.,Isobe, A., Jongedijk, C.E., Kaandorp, M.L.A., Khatmullina, L., Koelmans, A.A.,Kukulka, T., Laufkotter, C., Lebreton, L., Lobelle, D., Maes, C., MartinezVicente, V., Maqueda, M.A.M., Poulain-Zarcos, M., Rodriguez, E., Ryan, P.G.,Shanks, A.L., Shim, W.J., Suaria, G., Thiel, M., van den Bremer, T.S., Wichmann, D., 2020. The physical oceanography of the transport of floating marine debris.Environ. Res. Lett. 15 (2), 32.

48. Wang, D., Su, L., Ruan, H.D., Chen, J., Lu, J., Lee, C.H., Jiang, S.Y., 2021. Quantitative and qualitative determination of microplastics in oyster, seawater and sediment from the coastal areas in Zhuhai, China. Mar. Pollut. Bull. 164, 112000 https://doi.org/10.1016/j.marpolbul.2021.112000.

49. Wicaksono, E.A., Werorilangi, S., Galloway, T.S., Tahir, A., 2021. Distribution and seasonal variation of microplastics in tallo river, Makassar, eastern Indonesia. Toxics 9, 1-13. https://doi.org/10.3390/toxics9060129.

50. Yaranal, N.A., Subbiah, S., Mohanty, K., 2021. Distribution and characterization of microplastics in beach sediments from Karnataka (India) coastal environments. Mar. Pollut. Bull. 169 https://doi.org/10.1016/j.marpolbul.2021.112550.

51. Zhang, C., Wang, S., Sun, D., Pan, Z., Zhou, A., Xie, S., Wang, J., Zou, J., 2020. Microplastic pollution in surface water from east coastal areas of Guangdong, South China and preliminary study on microplastics biomonitoring using two marine fish. Chemosphere 256, 127202. https://doi.org/10.1016/j.chemosphere.2020.127202.

52. Zhang, Y., Wen, X., Zhou, W., Yang, Y., Zhou, Z., Chen, J. & Yin, L. (2025). Retention and migration of micro-plastics in stepped paddy fields: A study on micro-plastic dynamics in the special irrigation system. *Environmental Research*, 120909.