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Microplastic Pollution in a Coastal Tourism Hub of West Bengal: A Geospatial Investigation of Mandarmani Beach and Its Environmental Implications

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Abstract

Introduction: The eastern coast of India is undergoing rapid commercialization, with tourism emerging as a major contributor to environmental degradation. Tourists often disregard waste management regulations, leading to increased meso- and microplastic pollution. Microplastics, now recognized as persistent contaminants of emerging concern, are widely present in marine, terrestrial, and atmospheric environments. However, data on their presence in tourism-driven beaches of West Bengal remains limited.

Methods: This study assessed the abundance, distribution, and composition of microplastics at Mandarmani Beach and adjacent coastal waters of the Bay of Bengal. Sediment and water samples were collected from 10 sampling points spanning fishing, tourism, and wastewater discharge zones. Visual and microscopic techniques were used to identify and categorize microplastics by shape and color. Chemical composition was determined using FTIR-ATR spectroscopy.

Results: Microplastics were detected in all samples, appearing as filaments, fibers, pellets, granules, foams, and films. Shapes included irregular, thread-like, square, and circular forms. Black (37.31%) and white (34.20%) were the most common colors, followed by yellow, red, and blue. FTIR-ATR analysis identified nine polymer types—PP, PE, PS, PETE, PTFE, PVC, PVP, PC, and PA—with polypropylene and polyethylene as the most dominant types.

Conclusion: This study provides the first evidence of microplastic pollution along Mandarmani Beach, revealing contamination from both land- and ocean-based sources. The findings highlight the urgent need for improved waste management, stricter enforcement of coastal regulations, and increased research on microplastic pathways to protect coastal ecosystems and public health.

Keywords: Microplastic pollution, Coastal contamination, Polymer characterization, Bay of Bengal, Marine ecosystem health

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Introduction

Primary microplastics are plastic fragments smaller than 5 mm that enter the environment directly, often found in products like toothpaste, cosmetics, and textiles, where they appear as microbeads or microfibers. Secondary microplastics, on the other hand, result from the degradation of larger plastic debris through physical, chemical, or biological processes—such as wave action, UV exposure, or microbial activity(1-4). Due to their large surface area, microplastics readily adsorb organic pollutants (e.g., PCBs, PAHs, pesticides) and inorganic contaminants (e.g., heavy metals) in aquatic ecosystems (5,6).

The presence of microplastics was first documented in the North Atlantic Ocean in the early 1970s (7). Since then, widespread plastic use and industrial practices, especially in fisheries and aquaculture, have contributed significantly to their abundance in marine habitats(8-10). Numerous studies have documented microplastic ingestion across taxa—including cetaceans, zooplankton, seabirds, fish, crustaceans, and bivalves (11-13). Ingestion occurs either through mistaken identity (14), foraging, or via trophic transfer (15). Though plastics are typically buoyant, chemical additives can alter their density, and biofilm formation may cause even lightweight particles to sink and attach to vegetation like eelgrass (16). Bacteria such as *Vibrio* and *Exiguobacterium* play key roles in this adhesion process . Microplastics thus span all trophic levels, affecting seabirds, fish, and ultimately humans through bioaccumulation and biomagnification. Plasticizers such as bisphenol A (BPA) are known endocrine disruptors(17). As fish form a major protein source globally, their contamination has raised critical concerns for human health (18).

India, the second-largest plastic waste producer globally, mismanages about 80% of its plastic waste (19). Rivers act as the main transport route of plastics to oceans. According to the 2024 Plastic Overshoot Day (POD) Report, India ranks second only to China in microplastic emissions, releasing approximately 391,879 tons into aquatic systems. The Ganga River—India's largest—contains the highest global concentration of microplastics among major rivers (19). In 2023, the Central Pollution Control Board formally acknowledged its presence in national water bodies. Several studies have documented microplastic pollution in India's marine ecosystems (11-13,20-31), with limited investigations focusing on West Bengal(32-34). Key sources of microplastics in coastal environments include tourism, untreated wastewater, and plastic manufacturing. Shoreline accumulation is often heterogeneous due to environmental transport mechanisms (35-37). The Bay of Bengal coastline, especially along Odisha, Andhra Pradesh, and West Bengal, receives high plastic loads from rivers such as the Ganges, Godavari, and Mahanadi. Despite increasing plastic use and poor waste regulation in this region, the eastern Indian coast remains critically understudied (38). The Ganga discharges an estimated 0.12 million tons of plastic annually, second only to the Yangtze River(39). Although various interventions, including the Ganga Action Plan (1985), the National River Conservation Plan, and the "Namami Gange Programme" (2014), were launched to improve water quality (40), a 2019 CPCB report found the river still unfit for human use due to continued pollutant influx(41). Recognizing these threats, regulatory actions have included bans on idol immersion, fines across Ganga basin states, and stricter discharge controls under the Environment Protection Act (1986) (40). Yet, microplastic accumulation persists(42)

Mandarmani, a coastal village in East Midnapore district, lies near Digha—one of West Bengal's most polluted beaches. Given Mandarmani's ecological sensitivity, growing tourism infrastructure, and the presence of multiple potential pollution vectors, this study aimed to characterize microplastic pollution along a relatively underexplored yet vulnerable coastal stretch of eastern India. Through field sampling, polymer identification, and spatial analysis, we assessed the density, composition, and distribution of microplastics across various beach zones. Polymer identification of microplastic particles was performed using Fourier-Transform Infrared (FTIR) spectroscopy in Attenuated Total Reflectance (ATR) mode. Spectra were acquired using a Bruker Alpha II FTIR spectrometer (Bruker Optics, Germany) equipped with a diamond ATR crystal. The aperture hole diameter was approximately 4 mm, and each spectrum was collected over a range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1}. Our central research question was to understand the extent and nature of microplastic pollution at Mandarmani beach, and how regional anthropogenic activities and weak governance structures contribute to this emerging environmental threat. The second question we addressed is: what are the spatial correlations between land-use patterns, tourism infrastructure, and microplastic hotspots along the Mandarmani coast? The study also explored how poor compliance with coastal regulations and unchecked tourism may accelerate environmental degradation, posing risks to both marine ecosystems and coastal communities.

Materials and Methods

Study Area

Mandarmani Beach, located along the East Midnapore district of West Bengal, lies on the northern coastline of the Bay of Bengal (Figure 1). Once a relatively undisturbed coastal stretch, it has witnessed a dramatic transformation over the last decade due to aggressive tourism development. The present study focused on five strategic sampling locations: North Mandarmani Point, Central Mandarmani Point, South Mandarmani Point, Estuary Point, and Fishing Village Point (Table 1). These points were selected to capture the influence of varied land-use zones, including tourist hotspots, natural estuarine discharge points, and local community fishing areas. In recent years, the region has experienced unregulated and often illegal construction of resorts and hotels, many of which violate Coastal Regulation Zone (CRZ) norms. These establishments frequently lack sewage treatment infrastructure, leading to direct discharge of untreated effluents into adjacent streams. The accompanying tourism-induced waste generation, poor waste segregation practices, and unrestricted coastal access have contributed to rising plastic litter, much of which breaks down into secondary microplastics.

Sample Collection from Marine Sediments, Preparation, and Analysis

Sediment samples were collected using a stainless-steel scoop. To prevent external contamination by microplastic particles, aluminum foil was used for sample storage. Upon transport to the laboratory, the samples were placed in a hot air oven and air-dried at 50°C until they attained a constant weight. The dried samples were sieved sequentially using mesh sizes of 10, 5, 500, 180, and 63 µm, thereby excluding mesoplastics, larger debris. To remove organic matter, as described by (43) the samples were treated with a solution comprising 60 ml of filtered hydrogen peroxide (H_2O_2, 30%; Merck, Sigma-Aldrich) diluted in 300 ml of distilled water. Density separation was subsequently performed using NaCl. The salt solution was added to the beakers, agitated for 1 hour, and then left to settle undisturbed for 24 hours. Due to density differences, all microplastics (MPs) rose to the uppermost layer of the water column. The supernatant was filtered

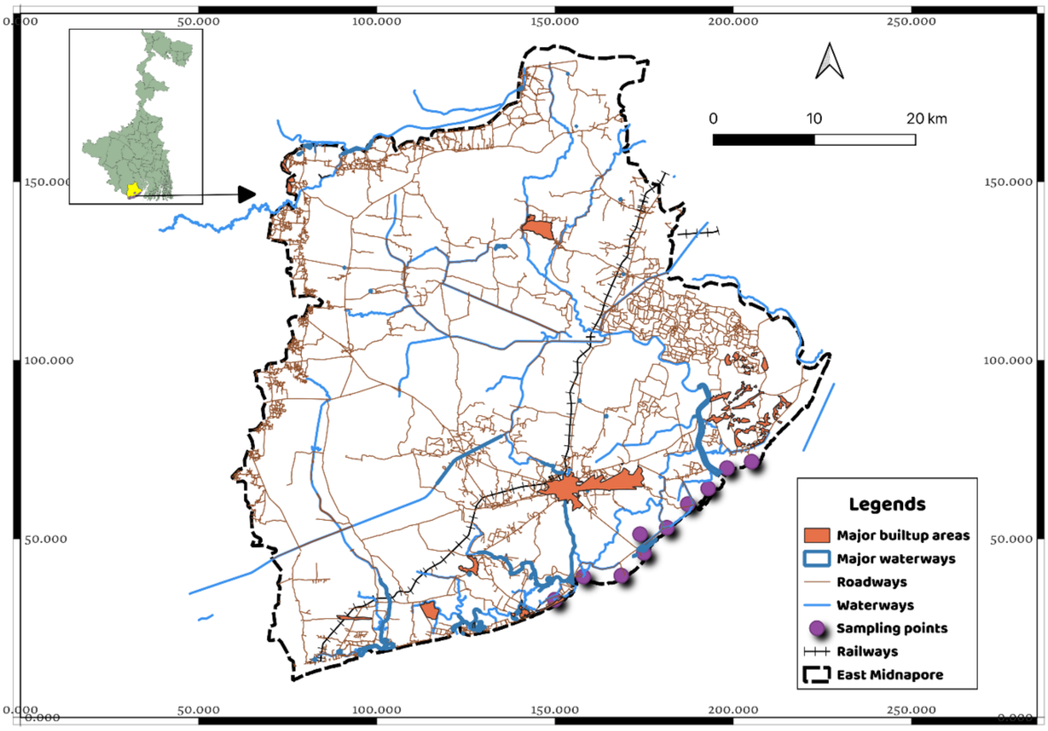

Figure 1. The study area map and sampling points at coastal Mandarmani, West Bengal

Table 1. Sampling locations from different zones and their key characteristics

Sampling Location	Sampling Points	Coordinates	Description
North Mandarmani Point	L8 L9 L10	21.6340° N, 87.6630° E	Located at the northern end of the beach, where the shoreline meets rocky formations. Acts as an indicator for investigating coastal erosion and marine biodiversity.
Central Mandarmani Point	L6 L7	21.6280° N, 87.6700° E	Situated in the middle of the beach, a tourist-heavy area. Useful for assessing the impact of human activities on the beach ecosystem.
South Mandarmani Point	L4, L5	21.6200° N, 87.6770° E	Located at the southern end, transitioning into a quieter area. Useful for studying sediment composition and local flora.
Estuary Point	L3	21.6350° N, 87.6800° E	Near the estuary where freshwater meets the sea, critical for understanding marine-freshwater interactions.
Fishing Village Point	L 1, L2	21.6300° N, 87.6650° E	Close to a local fishing village. Essential for studying socioeconomic aspects of coastal communities and their dependence on marine resources.

through Whatman filter paper (90 mm diameter, 20 µm pore size). The retained MPs were transferred to labeled Petri dishes and stored for visual analysis.

Sample Collection, Preparation, and Analysis of Marine Water

In June 2024, seawater samples were collected during both high and low tides. Following the standard methodology described by (44) stainless steel buckets were used to collect 0.15 m^3 (200 liters) of water at each sampling point (Table 1). Sampling occurred approximately 100 m from the shoreline, with each location spaced almost 200 m apart. The collected water was filtered through a mesh net with a pore size of 300 µm. The retained material was transported to the laboratory for further processing. In the laboratory, visual inspection was performed to remove any solid debris.

To ensure complete removal of organic matter, the protocol provided by (45) was followed. Samples were treated with Fenton's reagent, a mixture of ferrous sulfate and a 30% hydrogen peroxide solution, at 70°C. Density separation was carried out by adding a NaCl solution to the beakers, stirring for 1 hour, and allowing the mixture to settle for 24 hours. Given their lower densities, MPs accumulated in the upper layer of the solution. The supernatant was filtered through Whatman filter paper (90 mm diameter, 20 µm pore size). The separated MPs were placed in labeled Petri dishes for subsequent visual assessment.

Visual Analysis of Microplastics

Visual analysis of larger MPs was conducted during the sieving process. Differentiation of plastic particles was aided by their distinct coloration. MPs were manually extracted from each sample, transferred onto Petri dishes, and classified based on their color, shape, and morphology. The Petri dishes were placed beneath an optical microscope (OLYMPUS SM-100) for detailed examination and photographic documentation of the particles.

Polymer Characterization Analysis of Microplastics Via FTIR-ATR

Polymer characterization of MPs was conducted using attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR). Particles were randomly selected using sterile tweezers based on morphological characteristics (fragments, films, fibers, foams, beads, and pellets) and stored in Eppendorf tubes for analysis. Polymer identification followed the ATR-FTIR protocol provided by PerkinElmer's Frontier™ FT-IR system. Before each measurement, the diamond probe was thoroughly cleaned to avoid cross-contamination. Each particle was analyzed individually, and the resulting spectra were compared with a reference polymer library outlined by Soliz et al., 2024 (46). Polymers were identified based on their functional group composition, with an identification confidence threshold of ≥ 80% spectral match.

Polymer Hazard Index and Hazard Score Assignment

In the absence of abundance data (items·kg^{-1} sediment or items·m^{-3} water), a polymer-based hazard assessment was performed using a weighted Polymer Hazard Index (PHI) adapted from (47) Lithner and Dave 2011, which was also followed by later microplastic risk studies. Polymer hazard scores were assigned following the framework of (47) Lithner and Dave 2011 , which ranks polymers on a 1–10 scale based on monomer toxicity and associated chemical hazards, supplemented with values from subsequent microplastic hazard literature. The scores applied in this study were: polyvinyl chloride (PVC) = 10, polystyrene (PS) = 9, polycarbonate (PC) = 8, polyamide (PA) = 6, polyethylene terephthalate (PETE) = 4, polytetrafluoroethylene (PTFE) = 3, polyvinylpyrrolidone (PVP) = 3 (approximate, based on low–moderate hazard classification in recent studies), polyethylene (PE) = 2, and polypropylene (PP) = 1. These values were used to calculate the Polymer Hazard Index (PHI) for sediment and water samples.

The PHI was calculated as: $PHI = \Sigma (f_i \times H_i)$, where f_i is the fraction of FTIR-identified spectra matching polymer i, and H_i is the hazard score assigned to that polymer. Hazard scores were derived from the study by Lithner and Dave 2011(47) for common polymers (PVC = 10, PS = 9, PC = 8, PA = 6, PETE = 4, PTFE = 3, PE = 2, PP = 1) and from microplastics literature for polymers with limited coverage (e.g., PVP = 3). This approach estimates the hazard potential of the polymer mix identified by FTIR rather than total exposure.

Results

Microplastics were identified at all 10 sampling sites, including sediment, sand, and marine water samples from Mandarmani Beach, West Bengal. The widespread presence of microplastics across these diverse matrices underscores the contamination of the coastal environment.

Composition and Morphological Characterization of Microplastics

Microplastics were detected in all sediment and water samples collected across the five study zones. Visual and microscopic examination revealed (Figure 2) a diversity of morphotypes—filaments, fibers, pellets, foams, films, and granules—with shapes ranging from irregular and thread-like to square and circular.

Color-based variation in microplastics across different sampling locations are presented in Figure 3.

FTIR-ATR-Based Polymer Identification

A total of 32 scans per sample were accumulated to improve

Figure 2. Shape-based variation in microplastics observed in the study

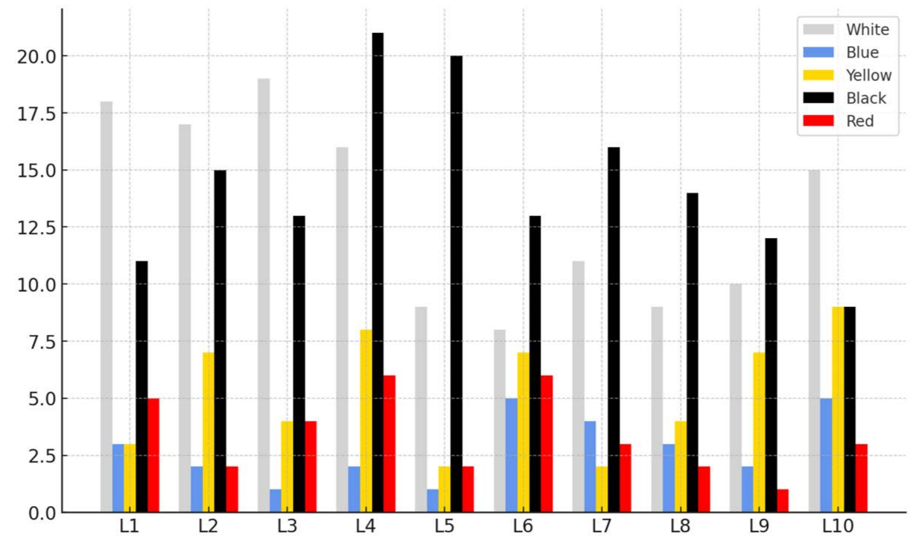

Figure 3. Color-based variation in microplastics across different sampling locations

signal-to-noise ratio, with each spectral acquisition taking approximately 1 minute. Background spectra were recorded before every new sample to ensure accuracy. Data processing and polymer matching were conducted using OPUS 7.5 software (Bruker) and compared against the Bruker polymer library, with a minimum match quality threshold of 70% used for identification.

Using FTIR-ATR spectroscopy, polymer characterization was carried out. Nine different polymers including Polypropylene (PP), Polyethylene (PE), Polystyrene (PS), Polyethylene Terephthalate (PETE), Polytetrafluoroethylene (PTFE), Polyvinyl Chloride (PVC), Polyvinylpyrrolidone (PVP), Polycarbonate (PC), and Polyamide (PA) were identified from the samples. The spectral graphs are represented in Figure 4, Figure 5 and Figure 6. To validate polymer identification, spectral matching was performed manually and cross-validated by comparing wavenumber peaks with reference spectra published by Soliz et al., 2024(46), who reported FTIR signatures of various microplastic types. While the study by Soliz et al., 2024(46) aided the interpretative process, only spectra derived from our own samples are presented in this study to ensure originality and accuracy. Peaks indicative of CH_2 bending (~720 cm^{-1}), C–H stretching (~2915 and 2849 cm^{-1}), and

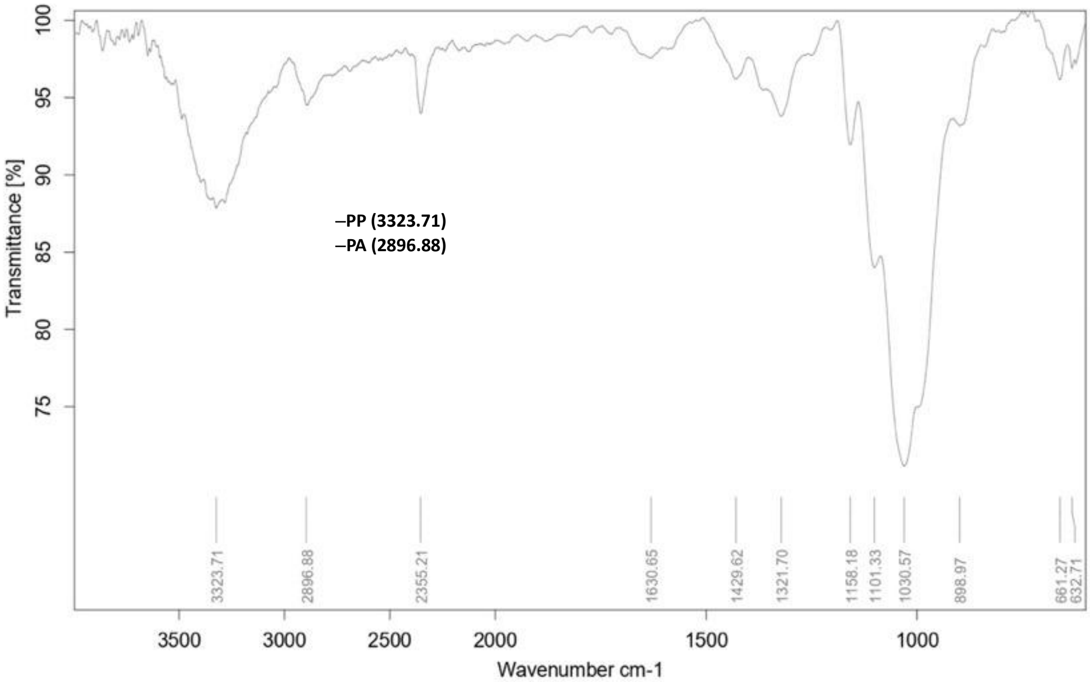

Figure 4. FT-IR spectra of the polymers (PP, PA) identified in the sand samples from Mandarmani

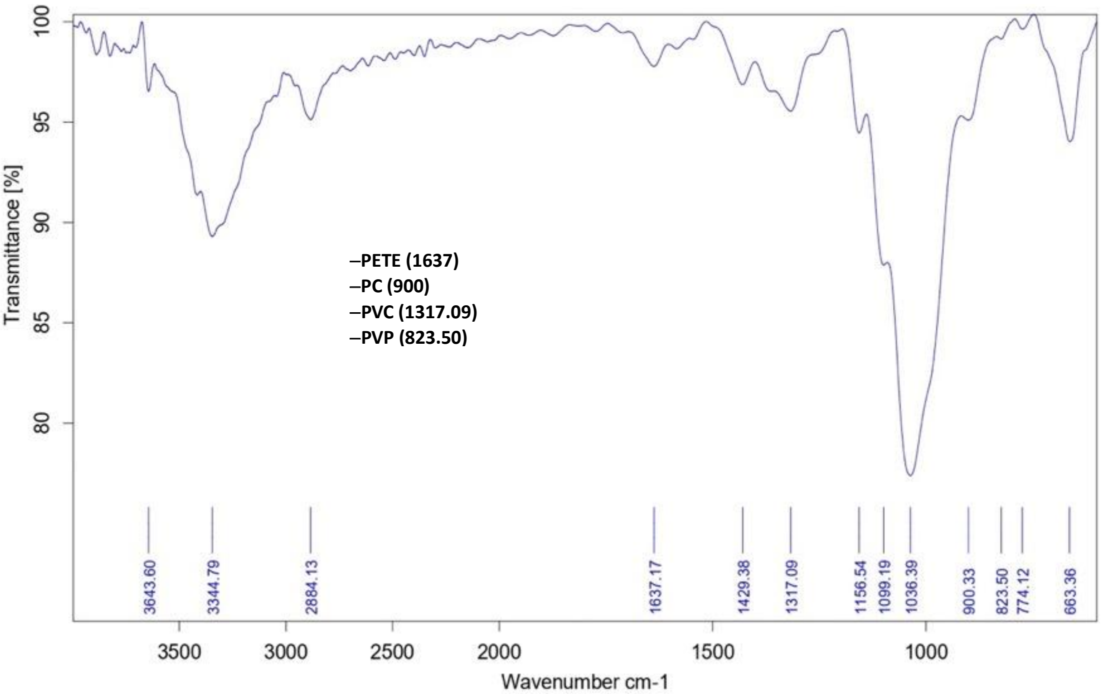

Figure 5. FT-IR spectra of the polymers (PETE, PC, PVC, and PVP) identified in coastal waters of Mandarmani

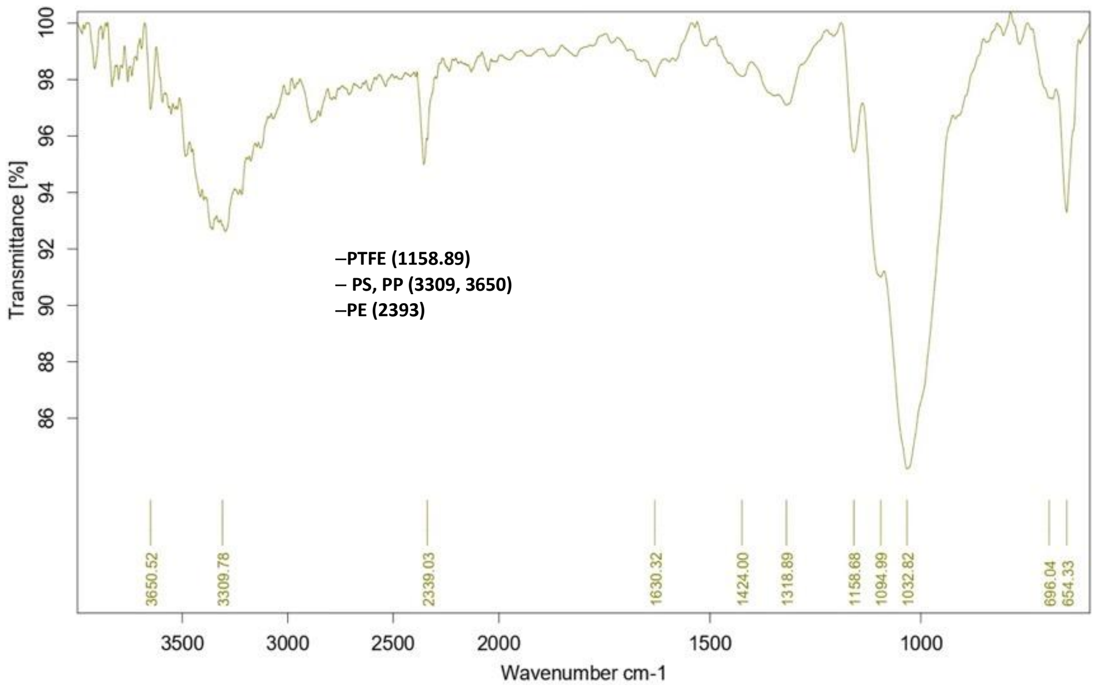

Figure 6. FT-IR spectra of the polymers (PTFE, PS, PE, and PP) identified in the sediments of Mandarmani

C = O stretching (~1715 cm^{-1}), among others, were used to distinguish between PE, PA, PETE, PS, and other polymers. Bruker OPUS 7.8 software facilitated baseline correction, peak identification, and spectral comparison.

Statistical Analysis

Statistical analyses, including Chi-square tests for associations between polymer type and microplastic shape/color, and one-way ANOVA for comparing microplastic diversity across functional beach zones, were performed using IBM SPSS Statistics (version 27) with a significance threshold set at $\alpha = 0.05$. A Chi-square test was conducted to examine the associations between polymer type and microplastic shape, as well as between polymer type and color. The test for polymer vs. shape yielded a test statistic of 33.75, with a p-value of 0.383, indicating no statistically significant association ($P > 0.05$). This suggests that the polymer type and shape are independent, meaning that no specific polymer is significantly more likely to have a particular shape. Similarly, the test for polymer vs. color resulted in a test statistic of 40.0 with a P-value of 0.157, also indicating no significant relationship ($P > 0.05$). These results imply that different polymers do not show a clear preference for specific colors, further supporting the hypothesis that the color distribution among microplastic polymers is random rather than driven by the polymer composition.

One-way analysis of variance (ANOVA) revealed a statistically significant difference in microplastic diversity among the three designated zones: (a) fishing zone, (b) recreation and tourism zone, and (c) wastewater discharge zone with beach markets and tourism ($P = 0.023$, $\alpha = 0.05$). These results indicate that microplastic diversity is not uniformly distributed across the studied zones, suggesting that anthropogenic activities specific to each area may influence the composition and distribution of microplastic pollution. The higher microplastic diversity in certain zones may be attributed to distinct sources of plastic waste, such as fishing gear residues, tourism-related litter, or wastewater effluents. The concentration of microplastics is closely associated with population density and various anthropogenic activities (5). This area is a well-known tourist destination that experiences considerable human impact. Additionally, coastal hotels discharge sewage into the surrounding environment, leading to contamination of both the water and beach sand. During low tide, this pollution becomes more apparent and is often accompanied by a strong, unpleasant odor.

Environmental Risk Assessment with Polymer Hazard Index

The PHI for sediments was 3.94 (n = 70 spectra), with polyamide (PA) and polystyrene (PS) as the largest contributors to hazard potential. The PHI for water samples was 5.03 (n = 67 spectra), driven predominantly by polyvinyl chloride (PVC) and polycarbonate (PC). Applying conservative thresholds (PHI < 2 = low, 2–4 = moderate, > 4 = high hazard potential), sediments fell into the moderate hazard category, while water samples were classified as high hazard. Table 2, Table 3, and Figure 7 show polymer-wise contributions to PHI.

Discussion

Classification of Microplastics Based on Shape

Microplastics exhibiting a variety of morphologies—such as filaments, fibers, pellets, granules, foams, thin sheets, and films as observed in this study, displayed diverse structural characteristics, including irregular, square, oval, elongated, thread-like, and circular forms (Figure 2). These forms indicate multiple sources, both land-based

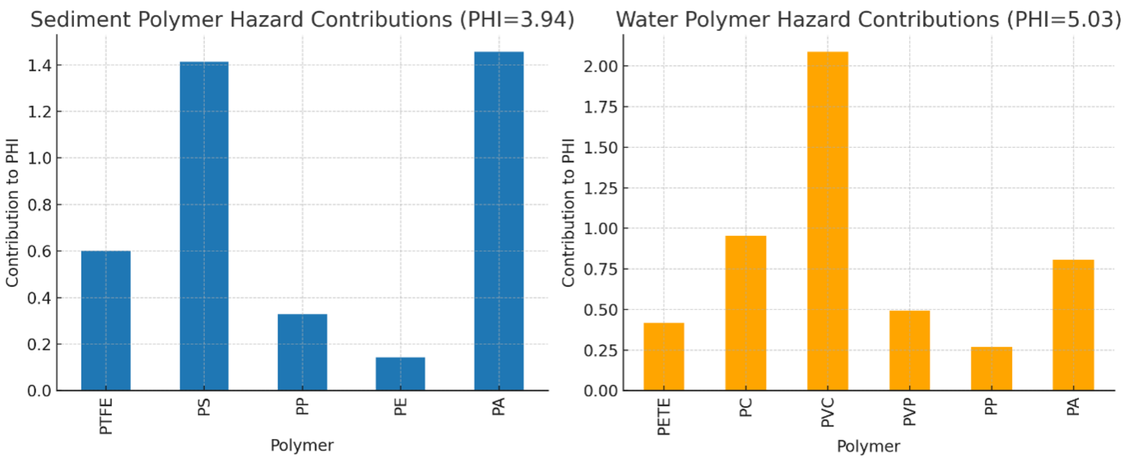

Figure 7. The Polymer Hazard Index (PHI) of the polymers identified from sediment and water samples, respectively

Table 2. Polymer counts, proportions, hazard scores, and PHI contributions in sediment samples

Polymer	Count	Percentage of FTIR subset (%)	Hazard score	Contribution to PHI (% × score)
PTFE	14	0.2000	3	0.6000
PS	11	0.1571	9	1.4143
PP	23	0.3286	1	0.3286
PE	5	0.0714	2	0.1429
PA	17	0.2429	6	1.4571
Total	**70**	**100%**	—	**PHI ≈ 3.9429**

Table 3. Polymer counts, proportions, hazard scores, and PHI contributions in water samples

Polymer	Count	Percentage of FTIR subset (%)	Hazard score	Contribution to PHI
PETE	7	0.1045	4	0.4180
PC	8	0.1194	8	0.9552
PVC	14	0.2090	10	2.0901
PVP	11	0.1642	3	0.4926
PP	18	0.2687	1	0.2687
PA	9	0.1343	6	0.8060
Total	**67**	**100%**	—	**PHI ≈ 5.030**

(e.g., packaging waste, textile fibers) and ocean-based (e.g., fishing gear, maritime debris). All these factors are prevalent in Mandarmani, which, as an active fishing harbor and a popular tourist destination, has experienced escalating plastic pollution over the past two decades due to the proliferation of resorts. Fibers and filaments, typically associated with synthetic textiles and fishing equipment, were among the most dominant forms, pointing to substantial input from laundry effluents and maritime industries. The detection of pellets and granules, commonly linked to primary microplastics from industrial origins, further supports the conclusion that both primary and secondary microplastics contribute to contamination in the region.

Classification of Microplastics Based on Color

The microplastics retrieved from the study area exhibited a range of colors, with white, black, yellow, red, and black as the most frequently observed colors that is represented in Figure 3 across different sampling points from the location. Colour analysis showed that black (37.31%) and white (34.20%) particles dominated across most samples, followed by yellow, red, and blue. Dark-coloured microplastics are often associated with weathered or aged fragments from packaging and tire dust, while lighter colours could stem from personal care products, ropes, and synthetic foams. The prevalence of black and white microplastics suggests the degradation of commonly used plastic materials, such as packaging, fishing nets, and synthetic textiles. Yellow and red microplastics, although less abundant, may originate from colored plastic products, such as bottle caps, industrial coatings, and synthetic fibers. The color variation also has ecological significance, as certain hues may increase the likelihood of ingestion by marine organisms due to their resemblance to natural food sources.

Classification of Microplastics Based on Polymer Type and Comparison with Previous Studies

A total of nine different polymers identified from the samples show that PP and PE were the most prevalent forms, highlighting their widespread use in consumer products, packaging materials, and fishing gear. Notably, both PP and PE are low-density polymers and tend to remain buoyant in marine waters, which explains their widespread presence across both sediment and water samples. Their dominance further highlights the role of plastic litter from tourist activities and hotel discharges, as these materials are commonly used in items like disposable cups, bags, and bottles. A comparable finding was documented along the beaches of India's southeast coast (18,45,48,49), where PP, PE, and PS were identified as the predominant polymer types. Studies from Goa (11) and the Southeast coast of India (48) also reflect similar dynamics, where increasing beach tourism correlates with higher proportions of PP, PE, and PS, affirming that tourism is a growing but under-addressed driver of microplastic pollution in Indian coastal states. It was reported by (50) and (51) that there was a high abundance of PE, PP, and PS in sediment samples from Chennai's Marina Beach and Besant Nagar regions, also characterized by intense anthropogenic activity and poor waste management. The polymer profile and morphotypes identified in this study are broadly consistent with the findings from other Indian coastal environments. However, while Chennai's microplastic pollution has been attributed to municipal sewage, industrial effluents, and densely urbanized drainage systems, the Mandarmani coastline presents a distinctly tourism-driven microplastic scenario, with impacts stemming from poorly regulated construction, hotel-based sewage discharge, and tourist litter. The overlap of high microplastic presence with zones of illegal resorts and drainage channels, as shown in Figure S1, suggests that microplastic pollution here is not only a consequence of volume but of concentrated human activity in sensitive coastal zones.

Violation of Coastal Regulation Norms and Spatial Mapping of Tourism-Driven Microplastic Pathways & Their Interpretation

Figure S2 underscores a pressing spatial association between the expanding built-up areas of Mandarmani and the potential conduits for microplastic dissemination along its coastal landscape. The visualization indicates that key transport infrastructures, comprising both man-made roads and natural watercourses, cut through zones experiencing rapid urban growth. Notably, the Central, South, and Estuary Points (Table 1) emerge as hotspots of concentrated development, marked by a surge in hospitality establishments such as hotels and resorts. The unchecked rise of informal and unregulated constructions in these areas amplifies the vulnerability of the coastal ecosystem to pollution influx, particularly through land-sea transfer pathways active during runoff events. Many of these hotels and resorts have been established in clear violation of Coastal Regulation Zone (CRZ) norms, often occupying buffer zones meant for ecological protection. Crucially, these unauthorized constructions frequently overlap with or obstruct existing drainage networks. This intersection intensifies the potential for pollutants, including microplastics, to be mobilized during periods of high rainfall or tide-induced flooding. Tourism-driven coastal areas are major hotspots for plastic waste generation, especially where infrastructure is inadequate to manage seasonal surges in waste (52). Citing a 2022 National Green Tribunal (NGT) order, hoteliers from Mandarmani have petitioned the Calcutta High Court to overturn a decision made by the chairperson of the district-level committee for the West Bengal Coastal Regulation Zone Authority (WBCZMS), which ordered the demolition of "illegal constructions" on the beach that were allegedly in violation of coastal guidelines (53).

The drainage channels visible on the map as blue lines run adjacent to or beneath these structures, making them susceptible to contamination from untreated sewage, greywater, and surface waste. During the monsoon season, the roads act as impermeable conduits, accelerating runoff and washing accumulated litter, synthetic debris, and microplastic fragments into nearby streams, which eventually discharge into the ocean. In particular, the Estuary Point shows strong hydrological connectivity between inland settlements and the marine system, a finding supported by the high microplastic presence in samples from this zone. Meanwhile, the Fishing Village Point exhibits moderate concentrations, likely due to both fishing-related plastic use and runoff from adjacent informal settlements.

Furthermore, roads lined with small shops, eateries, and tourist vendors contribute significantly to single-use plastic littering. These roads directly link with beach access points, providing a clear and unbroken plastic pollution pathway from inland sources to the shoreline. The presence of PP and PE in the marine samples further supports this inference, as these polymers are commonly found in food packaging and disposable tourist goods. Together, the co-occurrence of poorly managed tourism infrastructure, active hydrological networks, and road connectivity has created a highly vulnerable microplastic loading zone at Mandarmani. The spatial pattern, as evident in Figure S2, is not coincidental but indicative of systemic environmental mismanagement, where unregulated urbanization has reshaped natural drainage systems into high-risk pollution corridors.

The Coastal Regulation Zone (CRZ) rules, notified under the Environment (Protection) Act, 1986, were established to conserve ecologically sensitive coastal areas and regulate unplanned development. As per the CRZ Notification, 2011, and its subsequent amendments, CRZ-III areas such as Mandarmani—must maintain a No Development Zone (NDZ) of 200 meters from the High Tide Line (HTL), with only restricted development permissible up to 500 meters inland (54). However, Mandarmani, a rapidly expanding beach tourism destination on the West Bengal coast, has witnessed significant non-compliance, with numerous resorts and hotels illegally constructed within the prohibited 200-meter zone(55). These developments often lack proper sewage and solid waste management infrastructure, contributing to the unchecked discharge of plastic waste into coastal waters. As a result, microplastic contamination has become increasingly prevalent in this region, especially during the monsoon, when runoff transports accumulated plastic debris from built-up zones to the sea (56).

The buffer analysis in Figure S1 clearly illustrates how many of these tourist structures encroach upon ecologically sensitive estuarine zones and drainage lines, intensifying the land-to-sea transport of microplastics. In the figure, the 200-meter zone is highlighted in red, whereas 500 meters is orange, subsequently 1 km is highlighted in yellow, and lastly, 3 km radius is highlighted in green. The failure to enforce CRZ norms has therefore allowed unsustainable tourism development to directly compromise coastal ecological integrity, exacerbating plastic pollution and posing risks to marine biodiversity and human health (51).

The inclusion of a Land Use–Land Cover (LULC) map in Figure S3 for the Mandarmani coastal stretch serves as a vital spatial validation tool for interpreting anthropogenic drivers behind microplastic pollution. The map highlights a pronounced conversion of natural land cover, such as coastal vegetation and barren sandy areas, into built-up zones over the past decade, particularly around the Central and Southern Mandarmani coastline. This transformation aligns spatially with the zones of intensified tourism infrastructure, corroborating observations from field surveys and remote sensing-based cluster analyses (Figure S1, Figure S3). The LULC data substantiate how rapid and unregulated urbanization has intensified land–sea connectivity via impervious surfaces and altered drainage patterns, thereby exacerbating surface runoff and waste discharge into marine zones. This land conversion not only violates Coastal Regulation Zone (CRZ) norms but also reinforces the relationship between human-induced land modifications and elevated microplastic accumulation in sensitive coastal environments.

Environmental and Public Health Implications

The presence of polymers such as PVC, PS, and PETE, known to leach harmful additives like phthalates, bisphenols, and flame retardants, indicates potential ecological toxicity. Estuarine and intertidal fauna, such as benthic invertebrates, crabs, and fish that feed or reside in sediment-rich environments, are at risk of ingesting microplastics, potentially leading to digestive blockages, false satiation, or bioaccumulation. As the Estuary Point connects freshwater runoff to marine inflows, these organisms may act as vectors for plastic transfer across ecological compartments. The detection of microplastics in zones near the Fishing Village Point raises concerns over seafood contamination.

According to an official, the NGT requested that 140 hotels be demolished because they were situated near the sea, after the DN of East Midnapore ordered their demolition for violating environmental standards and coastal regulation zone rules. Since Mandarmani is regarded as a preferred tourist place during the winter, the state has decided against the demolition (57,58). The NGT notified that if they were not demolished, legal actions would be taken (59).

Conclusion

This study highlights significant microplastic (MP) contamination in the sediments of Mandarmani Beach, driven by tourism, fishing activities, commercial operations, and inadequate waste management, and calls for an urgent check on illegal tourism constructions. The area's dual role as both a recreational hotspot and a hub for fishing and transit contributes to the accumulation of microplastics, especially from improperly disposed waste and effluents. Chronic exposure risks are likely for local residents who depend on marine resources for food and livelihood, with contaminated seafood and potential dermal contact posing health concerns. The region's vulnerability is further exacerbated by plastic waste inflow from major rivers such as the Ganges, Mahanadi, and Godavari, which carry urban and rural debris into the Bay of Bengal. Coupled with increasing plastic use in nearby densely populated states and poor disposal infrastructure, these factors amplify the threat to coastal ecosystems. The findings call for urgent mitigation strategies targeting MP sources, improved waste management, and expanded research into the transport, accumulation, and ecotoxicological effects of microplastics on native fauna and human health.

The generation of sustainable schemes and policies is never enough if these are not implemented at the grassroots levels through public awareness and people's participation. Community outreach programs and activities such as seminars, workshops, conferences and events have been organized by the Namami Gange Program. Various awareness drives have been planned in the form of rallies, cleanliness drives, exhibition programs, awareness campaigns, etc. Social media helps spread public awareness and increases the visibility of these programs to larger masses. However, there is a knowledge gap between the policies to be implemented and the management of microplastic removal programs. Intervention from local administrators and NGOs can help resolve the major problems of microplastic pollution in rivers. The same could also be implemented in open water areas. At the 4th Intergovernmental Negotiating Committee (INC-4) session on a global plastics treaty, India began reassessing the full life cycle of plastic amid growing concerns over the health risks of microplastic additives. Though a relatively low plastic polluter, the 2024 POD report urged India to strengthen its waste management infrastructure and adopt long-term measures like extended producer responsibility (EPR) to curb plastic pollution in waterways.

To effectively minimize the generation of microplastics, a multipronged approach involving individuals, industries, and policymakers is essential. The microplastic burden revealed in this study strongly supports the need for multi-scalar interventions such as Coastal Regulation Zone (CRZ) enforcement, mandatory sewage treatment and waste management infrastructure, seasonal monitoring frameworks, and public awareness campaigns targeting tourists and local businesses. Reducing single-use plastics through reusable alternatives and regulatory policies can significantly reduce plastic waste. Encouraging the use of natural fiber textiles over synthetic materials and supporting sustainable brands will help reduce microfiber pollution. Strengthening waste management systems, including enhanced recycling programs and public awareness campaigns, is crucial in preventing plastic leakage into the environment. Additionally, investing in research and innovative solutions, such as biodegradable materials and plastic degradation technologies, will support long-term sustainability. Strong policy advocacy and international cooperation, along with educational awareness in schools, are necessary to enforce regulations, promote sustainable practices, and foster behavioral change. Implementing these strategies collectively can significantly mitigate microplastic pollution and its environmental impact.

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All authors declared no competing interests.

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Supplementary files
Supplementary file 1 contains Figures S1-S3.

References
1. Amrutha K, Warrier AK. The first report on the source-to-sink characterization of microplastic pollution from a riverine environment in tropical India. Sci Total Environ 2020;739:140377. doi:10.1016/j.scitotenv.2020.140377
2. Dawson AL, Kawaguchi S, King CK, Townsend KA, King R, Huston WM, et al. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat Commun 2018;9(1):1001. doi:10.1038/s41467-018-03465-9
3. Dussud C, Ghiglione JF. Bacterial Degradation of Synthetic Plastics. 2014. Available from: https://667-per-cm.net/wp-content/uploads/2019/05/bacterialdegredationofsyntheticplastics-dussud-ghiglione.pdf.
4. Mateos-Cárdenas A, O'Halloran J, van Pelt F, Jansen MAK. Rapid fragmentation of microplastics by the freshwater amphipod *Gammarus duebeni* (Lillj.). Sci Rep 2020;10(1):12799. doi:10.1038/s41598-020-69635-2
5. Wang MH, He Y, Sen B. Research and management of plastic pollution in coastal environments of China. Environ Pollut 2019;248:898-905. doi:10.1016/j.envpol.2019.02.098
6. Xie H, Chen J, Feng L, He L, Zhou C, Hong P, et al. Chemotaxis-selective colonization of mangrove rhizosphere microbes on nine different microplastics. Sci Total Environ 2021;752:142223. doi:10.1016/j.scitotenv.2020.142223
7. Carpenter EJ, Smith KL Jr. Plastics on the Sargasso Sea surface. Science 1972;175(4027):1240-1. doi:10.1126/science.175.4027.1240
8. Andrady AL. Microplastics in the marine environment. Mar Pollut Bull 2011;62(8):1596-605. doi:10.1016/j.marpolbul.2011.05.030
9. Watson SCL, Paterson DM, Queirós AM, Rees AP, Stephens N, Widdicombe S, et al. A conceptual framework for assessing the ecosystem service of waste remediation: in the marine environment. Ecosyst Serv 2016;20:69-81. doi:10.1016/j.ecoser.2016.06.011
10. Hinojosa IA, Thiel M. Floating marine debris in fjords, gulfs and channels of southern Chile. Mar Pollut Bull 2009;58(3):341-50. doi:10.1016/j.marpolbul.2008.10.020
11. Naidu SA, Ranga Rao V, Ramu K. Microplastics in the benthic invertebrates from the coastal waters of Kochi, Southeastern Arabian Sea. Environ Geochem Health 2018;40(4):1377-83. doi:10.1007/s10653-017-0062-z
12. Kumar P. Role of plastics on human health. Indian J Pediatr 2018;85(5):384-9. doi:10.1007/s12098-017-2595-7
13. Karuppasamy P, Kamalesh T, Anitha K, Pandian MS, Ramasamy P, Verma S. Design and growth of novel organic molecular Quinoline 4-nitrophenol (QNP) single crystals: for nonlinear optical (NLO) applications. J Mol Struct 2020;1210:128036. doi:10.1016/j.molstruc.2020.128036
14. Rossi LC, Scherer AL, Petry MV. First record of debris ingestion by the shorebird American Oystercatcher (*Haematopus palliatus*) on the Southern coast of Brazil. Mar Pollut Bull 2019;138:235-40. doi:10.1016/j.marpolbul.2018.11.051
15. Jovanović B. Ingestion of microplastics by fish and its potential consequences from a physical perspective. Integr Environ Assess Manag 2017;13(3):510-5. doi:10.1002/ieam.1913
16. Zhao S, Wang C, Bai B, Jin H, Wei W. Study on the polystyrene plastic degradation in supercritical water/CO2 mixed environment and carbon fixation of polystyrene plastic in CO2 environment. J Hazard Mater 2022;421:126763. doi:10.1016/j.jhazmat.2021.126763
17. Lusher AL, McHugh M, Thompson RC. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar Pollut Bull 2013;67(1-2):94-9. doi:10.1016/j.marpolbul.2012.11.028
18. Mandal A, Singh N, Mondal A, Talib M, Basu R, Biswas MK, et al. The extent of microplastic pollution along the eastern coast of India: focussing on marine waters, beach sand, and fish. Mar Pollut Bull 2023;194(Pt B):115265. doi:10.1016/j.marpolbul.2023.115265
19. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv 2017;3(7):e1700782. doi:10.1126/sciadv.1700782
20. Reddy MS, Shaik B, Adimurthy S, Ramachandraiah G. Description of the small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India. Estuar Coast Shelf Sci 2006;68(3-4):656-60. doi:10.1016/j.ecss.2006.03.018
21. Jayasiri HB, Purushothaman CS, Vennila A. Plastic litter accumulation on high-water strandline of urban beaches in Mumbai, India. Environ Monit Assess 2013;185(9):7709-19. doi:10.1007/s10661-013-3129-z
22. Sruthy S, Ramasamy EV. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ Pollut 2017;222:315-22. doi:10.1016/j.envpol.2016.12.038
23. Krishnakumar S, Anbalagan S, Kasilingam K, Smrithi P, Anbazhagi S, Srinivasalu S. Assessment of plastic debris in remote islands of the Andaman and Nicobar Archipelago, India. Mar Pollut Bull 2020;151:110841. doi:10.1016/j.marpolbul.2019.110841
24. Vidyasakar A, Neelavannan K, Krishnakumar S, Prabaharan G, Sathiyabama Alias Priyanka T, Magesh NS, et al. Macrodebris and microplastic distribution in the beaches of Rameswaram Coral Island, Gulf of Mannar, southeast coast of India: a first report. Mar Pollut Bull 2018;137:610-6. doi:10.1016/j.marpolbul.2018.11.007
25. Robin RS, Purvaja R, Ganguly D, Hariharan G, Paneerselvam A, Sundari RT, et al. COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in a coastal megacity, Chennai, India. Mar Pollut Bull 2021;171:112739. doi:10.1016/j.marpolbul.2021.112739

26. Tiwari R, Azad N, Dutta D, Yadav BR, Kumar S. A critical review and future perspective of plastic waste recycling. Sci Total Environ 2023;881:163433. doi:10.1016/j.scitotenv.2023.163433
27. Nikki R, Abdul Jaleel KU, Ragesh S, Shini S, Saha M, Dinesh Kumar PK. Abundance and characteristics of microplastics in commercially important bottom dwelling finfishes and shellfish of the Vembanad Lake, India. Mar Pollut Bull 2021;172:112803. doi:10.1016/j.marpolbul.2021.112803
28. Patchaiyappan A, ZakiAhmed S, Dowarah K, Khadanga SS, Singh T, Jayakumar S, et al. Prevalence of microplastics in the sediments of Odisha beaches, southeastern coast of India. Mar Pollut Bull 2021;167:112265. doi:10.1016/j.marpolbul.2021.112265
29. Kumar V, Singh E, Singh S, Pandey A, Bhargava PC. Micro- and nano-plastics (MNPs) as emerging pollutant in ground water: environmental impact, potential risks, limitations and way forward towards sustainable management. Chem Eng J 2023;459:141568. doi:10.1016/j.cej.2023.141568
30. Velmurugan PM, Krishnan V, Devika PT. Baseline study on identification, characterization, distribution and abundance of microplastics in surface water from Ennore to Kovalam along the east coast of India. Phys Chem Earth (2002) 2023;130:103391. doi:10.1016/j.pce.2023.103391
31. Valsan G, Warrier AK, Anusree S, Tamrakar A, Khaleel R, Rangel-Buitrago N. Seasonal variation of microplastics in tropical mangrove waters of south-western India. Reg Stud Mar Sci 2024;69:103323. doi:10.1016/j.rsma.2023.103323
32. Sarkar DJ, Das Sarkar S, Das BK, Sahoo BK, Das A, Nag SK, et al. Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system. Water Res 2021;192:116853. doi:10.1016/j.watres.2021.116853
33. Kumar R, Sinha R, Refat Jahan Rakib M, Padha S, Ivy N, Bhattacharya S, et al. Microplastics pollution load in Sundarban delta of Bay of Bengal. J Hazard Mater Adv 2022;7:100099. doi:10.1016/j.hazadv.2022.100099
34. Moharana S, Dey S, Priyadarsini S, Kumar MS, Das AP. Identification and characterization of microplastic pollutants from the marine sediments of Paradeep coast of Bay of Bengal, India for their sustainable management. In: Das AP, Behera ID, Das NP, eds. Renewable Energy Generation and Value Addition from Environmental Microfiber Pollution Through Advanced Greener Solution. Cham: Springer; 2024. p. 57-73. doi:10.1007/978-3-031-51792-1_4
35. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, et al. Lost at sea: where is all the plastic? Science 2004;304(5672):838. doi:10.1126/science.1094559
36. Turra A, Manzano AB, Dias RJ, Mahiques MM, Barbosa L, Balthazar-Silva D, et al. Three-dimensional distribution of plastic pellets in sandy beaches: shifting paradigms. Sci Rep 2014;4:4435. doi:10.1038/srep04435
37. Crawford CB, Russell M, Ewins C, Quinn B. Chemical adsorption of hydrophobic polycyclic aromatic hydrocarbons in the marine environment onto microplastic polymers and subsequent desorption in a simulated gut. In: SETAC Europe 26th Annual Meeting. Nantes, France: La Cite Nantes Events Center; 2016.
38. Vanapalli KR, Sharma HB, Ranjan VP, Samal B, Bhattacharya J, Dubey BK, et al. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. Sci Total Environ 2021;750:141514. doi:10.1016/j.scitotenv.2020.141514
39. Sarkar DJ, Das Sarkar S, Vanniaraj SK, Kundu S, Das BK. Microplastic pollution in Ganga: present status and future need. Sci Cult 2022;88(11-12):400-5. doi:10.36094/sc.v88.2022
40. Biodiversity & Environment. 15-Point Directive to Clean Ganga. 2019. Available from: https://www.drishtiias.com/daily-news-analysis/15-point-directive-to-clean-ganga.
41. Toxics Link. Quantitative Analysis of Microplastics Along River Ganga. 2020. Available from: https://counterviewfiles.wordpress.com/wp-content/uploads/2021/07/quantitative-analysis-of-microplastics-along-river-ganga.pdf.
42. Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk KO, et al. A critical analysis of the biological impacts of plasticizers on wildlife. Philos Trans R Soc Lond B Biol Sci 2009;364(1526):2047-62. doi:10.1098/rstb.2008.0242
43. Yaranal NA, Subbiah S, Mohanty K. Distribution and characterization of microplastics in beach sediments from Karnataka (India) coastal environments. Mar Pollut Bull 2021;169:112550. doi:10.1016/j.marpolbul.2021.112550
44. Calcutt J, Nussbaumer A, Sluka R. Guidelines for sampling microplastics on sandy beaches. A Rocha International; 2018.
45. Masura J, Baker JE, Foster GD, Arthur C, Herring C. Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. NOAA Technical Memorandum NOS-OR&R-48. 2015. Available from: https://repository.library.noaa.gov/view/noaa/10296.
46. Soliz DL, Paniagua González G, Muñoz-Arnanz J, Bravo-Yagüe JC, Fernández Hernando P, Garcinuño Martínez RM. Identification and morphological characterization of different types of plastic microparticles. Heliyon 2024;10(11):e30749. doi:10.1016/j.heliyon.2024.e30749
47. Lithner D, Larsson A, Dave G. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci Total Environ 2011;409(18):3309-24. doi:10.1016/j.scitotenv.2011.04.038
48. Karthik R, Robin RS, Purvaja R, Ganguly D, Anandavelu I, Raghuraman R, et al. Microplastics along the beaches of southeast coast of India. Sci Total Environ 2018;645:1388-99. doi:10.1016/j.scitotenv.2018.07.242
49. Singh V, Chakraborty S, Chaudhuri P. Quantification and polymer characterization of sediment microplastics along the Golden Beach, Puri, India. Indian J Geo Mar Sci 2021;50(7):574-84.
50. Veerasingam S, Mugilarasan M, Venkatachalapathy R, Vethamony P. Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. Mar Pollut Bull 2016;109(1):196-204. doi:10.1016/j.marpolbul.2016.05.082
51. Ramasubramanian V, Shanmugam A, Ramesh R, Sivakumar R, Arulvasu C. Occurrence and distribution of microplastics in beach sediments along the Chennai coast, Southeast India. Mar Pollut Bull 2022;179:113662.
52. United Nations Environment Programme (UNEP). From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. Nairobi: UNEP; 2021.
53. Mittal Y. Unauthorised construction has to be demolished; judicial regularisation impermissible: Supreme Court. LiveLaw. Availble from: https://www.livelaw.in/supreme-court/kaniz-ahmed-versus-sabuddin-unauthorised-construction-demolished-judicial-regularisation-impermissible-290932
54. Chakraborty S, Chattopadhyay R. Coastal tourism and land-use transformation in Mandarmani, India. GeoJournal 2020;85(2):375-90.
55. CPCB. Coastal Pollution in India: Assessment and Recommendations. Ministry of Environment, Forest and Climate Change, Government of India; 2018.
56. Ministry of Environment and Forests. Coastal Regulation Zone Notification. Government of India; 2011. Available from: https://cat.org.in/wp-content/uploads/2016/07/CRZ-Notification-2011-06.01.2011.pdf
57. Som M. Calcutta High Court Orders Interim Stay on Demolition of 'Illegal' Construction in the Beach Town of Mandarmani. The Hindu; 2024.
58. The Indian Express. Mamata Banerjee Revokes District Admin's Demolition Order to Raze 'Illegal' Hotels on Mandarmani Beach. The Indian Express; 2024.
59. The Times of India. No Bulldozer at Mandarmoni, Don't Jeopardise Tourism: CM to Admin. Times of India; 2024.