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Abundance, seasonal variation, and polymer analysis of microplastic pollution in the sediments of Mahim bay, Mumbai, India

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Abstract

Microplastic pollution has become an urgent global environmental concern, particularly in coastal areas where its adverse effects are pronounced. This study aims to assess the abundance, color distribution, shape distribution, and polymer type distribution of microplastics in Mahim Bay across different seasonal periods. Pre-monsoon concentrations averaged 1055.66 ± 92.981 (Mean ± SD, n=6) microplastic items per kilogram of dry weight, similar to global findings. During the monsoon, concentrations slightly increased to 1080.33 ± 326.79 (Mean ± SD, n=6) microplastic items per kilogram of dry weight, due to intensified hydrological processes. Post-monsoon, concentrations decreased significantly to 563 ± 198.31 (Mean ± SD, n=6) microplastic items per kilogram of dry weight, indicating changes in sediment dynamics. Color distribution varied among locations, with transparent, black and white microplastics being common. Fiber-shaped microplastics dominated, followed by fragments. Polyethylene (PE) and polypropylene (PP) were prevalent polymers. The study highlights seasonal variability in microplastic pollution dynamics and contributes to understanding its impact on marine ecosystems.

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Introduction

Microplastics, characterized as plastic particles measuring less than 5 millimeters, have risen as a pivotal environmental concern, particularly within marine ecosystems, heralding the onsets of the so-called "Plasticene Age" (Jonathan *et al.,* 2021; Azaaouaj *et al.,* 2024; Gupta *et al.,* 2024; Santucci *et al.,* 2024). As per the Plastics-the facts 2021 report, global plastic production reached a staggering 368 million tons in 2019. These minuscule plastic fragments stem from diverse origins, including the degradation of larger plastic debris, industrial processes, and the disintegration of synthetic textiles (Surana *et al.,* 2024; Thacharodi *et al.,* 2024). Upon entry into marine environments, microplastics present multifaceted threats to marine organisms (Ma *et al.,* 2020; Palmer *et al.,* 2021). They are susceptible to ingestion across a broad spectrum of marine life, from planktonic organisms to upper trophic level predators, inducing internal harm, obstructions, and disruptions to vital physiological functions (Sul *et al.,* 2014; Clark *et al.,* 2016). Furthermore, microplastics exhibit an inherent capacity for the adsorption and transportation of deleterious pollutants, such as heavy metals and organic compounds, thereby accentuating their impact as they ascend through the marine food web (Godoy *et al.,* 2019; Wang *et al.,* 2019). Moreover, their accumulation within marine sediments incites alterations to benthic habitats and perturbs nutrient cycling dynamics (Claessens *et al.,* 2011; Martin *et al.,* 2017). Mitigation strategies targeting microplastic pollution necessitate a comprehensive approach, entailing enhancements in waste management practices, the enforcement of stringent regulations governing plastic production and consumption, alongside the development and deployment of cutting-edge technologies for the detection and removal of microplastics within marine environments (Prata *et al.,* 2019; Onyena *et al.,* 2021). Immediate and concerted action is imperative to safeguard the ecological integrity of our oceans from the pervasive menace posed by microplastics. These fragmented microplastics, once liberated, exhibit the capability to traverse vast expanses of oceanic demesnes via complex oceanic currents and wind patterns, leading to their pervasive dispersal across marine ecosystems (Andrady, 2011; Jambeck *et al.,* 2015). The ingress of plastic pollution into marine environments occurs through various pathways, encompassing storm-water runoff, aerial deposition via wind currents, and riverine transport, with resultant accumulation within oceanic gyres accentuating the concentrations of plastic debris therein (Gupta *et al.,* 2024; Jambeck *et al.,* 2015). The diverse origins of microplastics within the marine milieu span from anthropogenic activities such as littering and improper disposal, to the incidental shedding of plastic particles from ubiquitous consumer products like synthetic textiles and tires (Schmidt *et al.,* 2018). Microplastics demonstrate remarkable resilience within aquatic habitats, persisting for prolonged durations, with marine sediments serving as prominent reservoirs for their long-term sequestration (Galloway *et al.,* 2017; Horton and Barnes, 2020).

Mahim Bay is an important coastal area located in Mumbai, Maharashtra, India (Noble and Keesari, 2021). It is situated along the Arabian Sea coast and serves as a prominent landmark in the city's geography. The bay stretches from Bandra in the north to Worli in the south, with Mahim Creek forming its narrow entrance where the Mithi River meets the sea (Varshney and Govindan, 1995). The bay is surrounded by densely populated urban areas and is characterized by a mix of natural and anthropogenic features. Mahim Bay is known for its diverse marine ecosystem, including mangroves, intertidal zones, and sandy beaches (Singare and Ferns, 2014).

It also holds cultural and historical significance, with landmarks such as Mahim Fort and Bandra-Worli Sea Link situated in its vicinity. The bay plays a vital role in the city's economy, serving as a hub for fishing activities, maritime transport, and recreational tourism. However, like many coastal areas worldwide, Mahim Bay faces environmental challenges such as pollution, habitat degradation, and coastal erosion, necessitating conservation efforts and sustainable management practices to preserve its ecological integrity for future generations (Singare *et al.,* 2014; Sapkale *et al.,* 2018). The present study aims to comprehensively examine the abundance, seasonal variation, and polymer composition of microplastic pollution within the sediments of Mahim Bay, Mumbai, India. Through systematic sampling campaigns conducted across different seasons, the study assessed the distribution and temporal dynamics of microplastics, considering factors such as monsoon influx and anthropogenic activities. Studies on microplastics in the sediments and Doma fish species of Mahim Bay have been recently conducted to better understand the extent of contamination in this coastal ecosystem (Sangeeta and Salunke, 2024a,b).

Laboratory analysis, including Fourier-transform Infrared Spectroscopy (FTIR), was employed to characterize the polymer types and sources of microplastics present in the sediments. By focusing on Mahim Bay, a significant coastal environment influenced by urbanization and industrialization, the study aimed at providing valuable insights into the extent of microplastic pollution in urban coastal areas and offer recommendations for effective mitigation strategies and further research avenues.

Materials and methods

Study area

The study area, Mahim Bay, constitutes a significant semi-enclosed segment of the Arabian Sea located in Mumbai, Maharashtra (Varshney and Govindan, 1995). It stretches from Bandra reclamation in the north to Worli in the south, with Mahim Creek serving as its narrow opening, where the Mithi River converges. Positioned within a semi-circle in the central region are Mahim Beach, Dadar Beach, and Prabhadevi Beach (Singare and Ferns, 2014). Six sampling locations were chosen within Mahim Bay for the evaluation of microplastic types and quantities within sediment: Spot A (19.048466° N, 72.835726° E), Spot B (19.043469° N, 72.838022° E), Spot C (19.0208° N, 72.8293° E), Spot D (19.0181° N, 72.8249° E), Spot E (19.0261° N, 72.8155° E) and Spot F (19.042689° N, 72.821024° E) (Fig. 1).

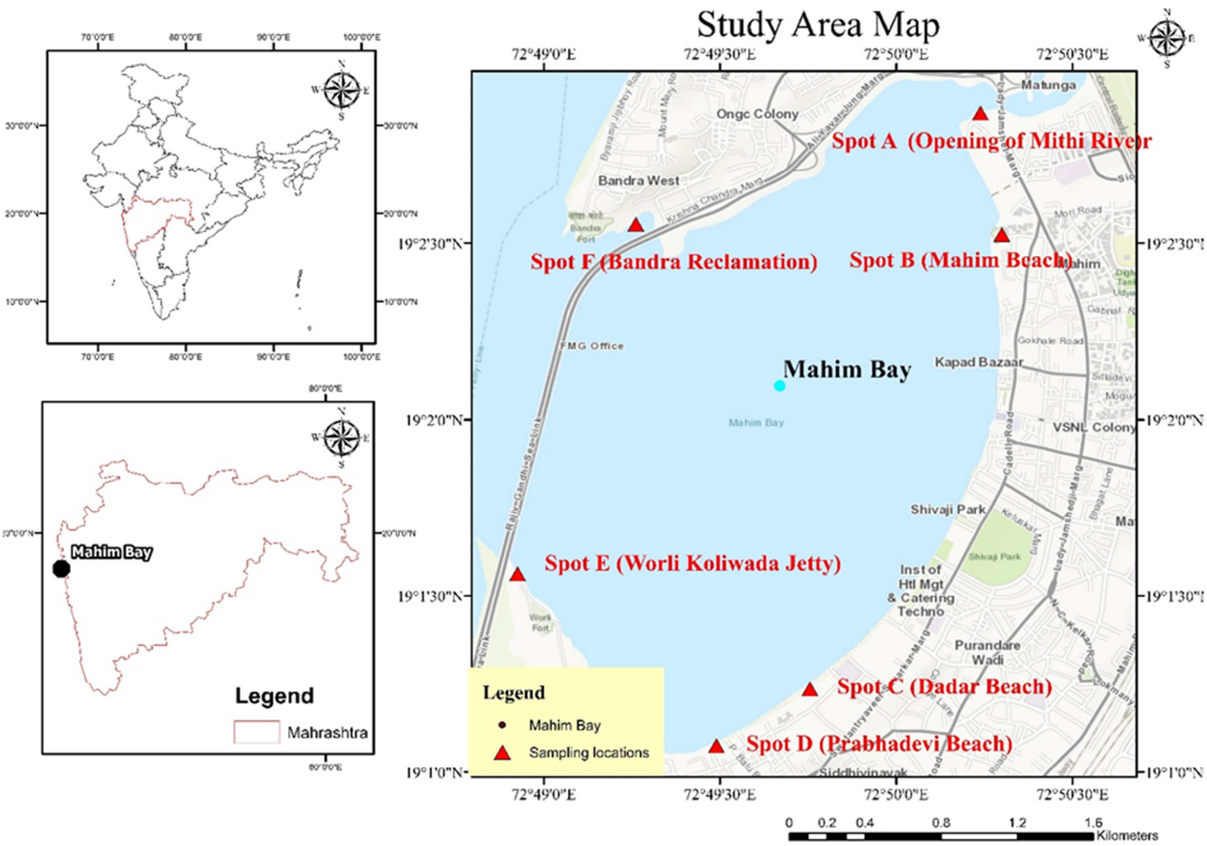

Fig. 1. Map of study area showing sampling spots along Mahim Bay

Sample collection and processing

Sampling occurred at specific locations: Spot A - at the opening of Mithi/Mahim creek beneath the Mahim causeway bridge, Spot B - Mahim Beach, Spot C - Dadar Beach, Spot D - Prabhadevi Beach, Spot E - Worli Koliwada Jetty, and Spot F - Bandra Reclamation. Samples were collected during the monsoon (August), post-monsoon (December), and pre-monsoon (May) periods between the years 2022-2023 from the intertidal zone, approximately two hours after high tide. A wooden frame, measuring 2 feet by 2 feet, was utilized meticulously for sediment sampling, ensuring the attainment of accurate and consistent measurements throughout the entirety of the procedure (Edwards and Glysson, 1988). This frame was placed on the sediment surface and gently pressed in, after which sediments were scooped from depths of 1 to 5 cm using a stainless-steel spoon. Sediment samples were then stored in aluminum foil containers, labeled, and brought to the laboratory for further analysis.

Upon arrival at the laboratory, the samples underwent an initial drying process in an oven at 60 degrees Celsius for six hours. Subsequently, they were sieved using a 5 mm mesh brass sieve to retain particles smaller than 5 mm in size, following recent protocols (Masura *et al.,* 2015; Veerasingam *et al.,* 2020). The subsequent steps involved a wet peroxide oxidation process conducted over two days. A 50-gram sediment sub-sample was subjected to peroxide oxidation with 30% hydrogen peroxide to remove organic matter (Nazir *et al.,* 2024). A 200 ml solution of sodium chloride with a density of 1.2 g/cm3 was added to facilitate the density separation of microplastics within the sample. The clear supernatant was filtered using a 0.45 µm cellulose nitrate Whatman filter paper GF/A (25 mm). The filter papers were air-dried and carefully transferred to Petri dishes for further examination.

Microscopic and polymer analysis using (FTIR)

Observation and classification of microplastics were conducted using a NIKON SMZ25 stereomicroscope, focusing on morphological structures, colors, and sizes. Microplastic particles were categorized based on their morphological structures such as fragments, fibers, films, pellets, and foam, as outlined in previous studies (Barnes, 2000; Andrady, 2011; Alomar *et al.,* 2017). Additionally, colors including black, blue, transparent, white, red, and silver were noted during classification.

The Fourier Transform Infrared (FTIR) protocol employed for polymer identification entails the utilization of a Spectrum instrument, characterized by model Spectrum 2 (serial number-87109), equipped with a MIR (Mid-Infrared) TGS detector and MIR source incorporating an OptKBr beamsplitter. Operational parameters are set with a resolution of 8 and a strong apodization function applied. The spectrum employing a ratio beam type with phase correction implemented in magnitude. Scan speed was established at 0.2, with a double IGram type utilized. Scanning direction is denoted as combined, and zero crossings were maintained at 0. An IR-Laser wavenumber of 11750.00 was applied with a JStop value of 8.94. The sample base plate utilized is a diamond Universal Attenuated Total Reflectance (UATR) accessory, exerting a force of 98 N and operating within a default scan range of 4000 to 450 cm-1. The ATR crystal combination is specified as diamond with a single bounce configuration. The specific UATR option remains unspecified. This methodological framework constitutes a rigorous and systematic approach for polymer identification through FTIR spectroscopic analysis, ensuring robust and scientifically sound outcomes (Pervez *et al.,* 2020).

Statistical analyses

The figures were generated utilizing the Origin Pro 2024 software package. To assess the potential relationship between seasonal variations and the abundance of microplastic particles, a statistical analysis of variance (one-way ANOVA) was conducted. This analysis aimed to elucidate whether distinct seasons exhibited significant differences in microplastic abundance, thereby providing insights into the seasonal dynamics of microplastic distribution.

Quality and assurance control

To ensure the integrity of sample collection, storage, processing, and analysis against airborne microplastic contamination, a stringent plastic-free protocol was rigorously enforced. All materials and equipment utilized were thoroughly vetted to be devoid of plastic components. The use of aluminum foils to cover samples minimized airborne particulate matter deposition, preserving study integrity by mitigating external microplastic contamination risks.

Environmental blanks, consisting of filter membranes saturated with deionized water filtered through a 1.6 µm filter, were systematically placed in the study environment to monitor potential contamination sources. Procedural blanks were prepared alongside samples to account for processing and analysis-related contamination. Rigorous cleaning protocols were implemented for glassware and tools, involving washing with dishwashing liquid, triple rinsing with 70% ethanol, and a final rinse with deionized water filtered through a 1.6 µm filter. These measures were informed by methodologies outlined in studies ensuring robust scientific validity and reliability (Brander *et al.,* 2020; Neelavannan *et al.,* 2022; Nazir *et al.,* 2024).

Results and discussion

Pre-monsoon

Abundance

In the present study, the analysis of sediment samples collected from Mahim Bay has yielded distinct concentrations of microplastics (MPs) across varying seasonal periods. During the pre-monsoon season, the analysis revealed an average concentration of 1055.66 ± 92.981 (Mean ± SD, n=6) per kilogram of dry weight. This finding underscores the pervasive presence of MPs within the sedimentary environment, indicative of potential ecological ramifications. Prior to the monsoon season, the investigation revealed notable disparities in microplastic pollution levels among the surveyed coastal locales. SPOT-A OPENING OF Mithi River displayed a discernible range, with concentrations spanning from 1110 to 1200 MPS items per kilogram of dry weight (DW), yielding an average of 1172.0 MPS items per kg of DW. Conversely, SPOT B-Mahim Beach displayed a narrower range, registering levels fluctuating between 1060 and 1200 MPS items per kg of DW, with an arithmetic mean of 1090.0 MPS items per kg of DW. SPOT C- Dadar Beach exhibited a broader spectrum, with values oscillating between 890 and 1200 MPS items per kg of DW and a mean concentration of 1067.6 MPS items per kg of DW. In contrast, SPOT D-Prabhadevi Beach presented a more constrained range, spanning from 910 to 960 MPS items per kg of DW, culminating in an average of 933.2 MPS items per kg of DW. The SPOT E- Worli Koliwada Jetty demonstrated a range of 180 MPS items per kg of DW, with concentrations varying from 890 to 1070 MPS items per kg of DW and an average of 972.0 MPS items per kg of DW. Likewise, SPOT F-Bandra Reclamation evinced a range between 890 and 1070 MPS items per kg of DW, averaging 975.2 MPS items per kg of DW (Fig. 9). These findings underscore the heterogeneity of microplastic pollution distributions across distinct coastal environments, underscoring the imperative for sustained surveillance and remedial interventions to mitigate this environmental challenge effectively.

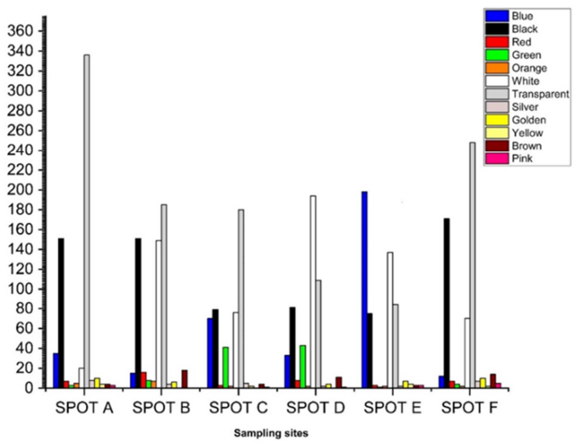

Fig. 2. Color distribution within microplastic pollution across the sampled locations during pre-monsoon

Colour and shape distribution

The examination of color distribution within microplastic pollution across the sampled locations revealed noteworthy disparities, with each locale presenting distinct compositions in terms of color categories (Fig. 2). At SPOT A - Opening of Mithi River, the predominant color was transparent, constituting a substantial 57.33% of the total count, followed by black at 25.77%.

Blue5.97%, white3.435%, green, red, golden made-up smaller proportions, at 0.512%, 1.95 %, and 1.76 % respectively, while silver accounted for1.365% of the observed microplastics. In SPOT B - Mahim Beach, the dominant colors shifted slightly, with transparent emerging prominently at 31.76%, alongside black at 25.77%, white (25.43%) brown 3.07%. Other significant contributors included blue, red, golden, orange, each comprising 2.55%, 2.73%, 1.024, 1.195%, respectively, among a diverse array of color distributions. This location showcased a more varied spectrum, with colors ranging from blue to pink, indicating potential multiple sources of microplastic pollution. At SPOT C- Dadar Beach, transparent microplastics were prevalent, constituting a striking 52.71% of the total count, followed by black at 13.05%, white 13% blue (11.94%), green 7% The presence of silver and red was also notable, at 0.84% and 0.51% respectively. This location exhibited a dominance of lighter colors, possibly reflecting the composition of plastic waste prevalent in the area. Moving further along the coast to SPOT D - Prabhadevi Beach, a similar pattern emerged, with white microplastics comprising 39.75% of the observed count, followed by transparent at 22.23%., black 16.6% blue 6.76%red 1.6%. While the distribution was relatively consistent with that of Dadar Beach, the less count of certain colors like orange was notable, suggesting potential variations in pollution sources or local environmental factors. At SPOT E - Worli Koliwada Jetty, the analysis of microplastic composition revealed a varied distribution of colors. The predominant hues were blue, comprising 38.15% of the sample, and black, accounting for 14.45%. Despite their dominance, other colors such as white (26.40%) and transparent (16.18%) featured prominently, adding complexity to the overall color spectrum. Minor proportions of red, green, orange, silver, golden, yellow, brown, and pink were also detected, contributing to the diverse range of colors observed. In SPOT F - Bandra Reclamation, the distribution of microplastic colors exhibited a notable prevalence of certain hues. Transparent microplastics were the most prominent, constituting 44.92% of the sample, followed by black at 30.98%. Additionally, white microplastics comprised a significant proportion, accounting for 12.68% of the total. Other colors such as blue (2.17%), red (1.26%), and brown (2.36%) were also observed, albeit in smaller quantities.

The analysis of shape distribution within the sampled microplastic pollution across various locations unveiled distinctive patterns and proportions, highlighting the diverse composition of pollutants present in each environment. At SPOT A - Opening of Mithi River, the predominant shape observed was fragment, constituting a significant 37.37% of the total count, followed by fiber at 35.15%. Film also contributed substantially, representing 19.11% of the observed microplastics. The presence of pellets and foam was relatively minor, making up only 3.07% and 5.29% respectively. This suggests a prevalence of thin plastic films and fibrous materials, possibly originating from packaging or textile sources. In SPOT B - Mahim Beach, a similar trend was observed, with fragment being the most prevalent shape, comprising 44.83% of the total count, followed closely by fiber at 21.82%. Film also featured prominently, constituting 15.20% of the observed microplastics. The presence of pellets (6.08%) and foam (10.73%) was relatively minimal. At SPOT C - Dadar Beach, fragment emerged as the dominant shape, constituting a substantial 42.98 % of the total count, followed by fibers at 36.71 %. Films also contributed significantly, comprising 15.55% of the observed microplastics. Pellets 3.02% and foam 1.72% constituted a smaller proportion, further emphasizing the prevalence of broken plastic pieces and thin films along the shoreline. Moving further along the coast to SPOT D - Prabhadevi Beach, a similar pattern was observed, with fragment being the predominant shape, constituting 47.74% of the total count, followed closely by fiber at 42.31%. Films also featured prominently, comprising 2.66% of the observed microplastics. Pellets and foam were relatively minor in comparison, indicating a prevalence of degraded plastic fragments and thin films in this coastal environment. At SPOT E - Worli Koliwada Jetty, fibers emerged as the predominant shape, constituting 44.12% of the total count, followed by fragments at 42.38%. Films also contributed significantly, comprising 6.93% of the observed microplastics. The presence of pellets and foam was relatively minimal, highlighting the prevalence of degraded plastic fragments and thin films in this urban coastal area. Lastly, at SPOT F - Bandra Reclamation, fragment was the most prevalent shape, constituting 43.29% of the total count, followed by fiber at 28.26%. Film also featured prominently, comprising 17.57% of the observed microplastics. Pellets and foam constituted a smaller proportion with percentages of 5.07%, 5.79% respectively, further emphasizing the prevalence of degraded plastic fragments and thin films along this coastal stretch (Fig. 3).

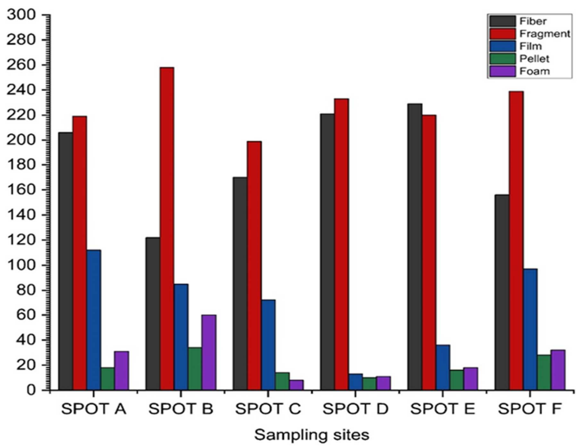

Fig. 3. Shape distribution within the sampled microplastic pollution across various locations during pre-monsoon

Polymer type distribution

An examination of the polymer types present in the sampled microplastic pollution across various locations reveals a diverse array of polymer compositions, each indicative of different sources and potential environmental impacts (Fig. 8). At SPOT A - Opening of Mithi River, the most prevalent polymer type observed was polyethylene (PE), followed by polypropylene (PP) and polystyrene (PS). Polyethylene terephthalate (PET) and ethylene-vinyl acetate (EVA) were also identified, albeit in smaller quantities. This suggests a variety of sources contributing to the microplastic pollution, including packaging materials and possibly industrial waste. In SPOT B - Mahim Beach, a similar pattern was observed, with PE being the most prevalent polymer type, followed by PP and PS, PET and EVA were also detected, albeit in smaller proportions. This indicates a comparable composition of microplastics to SPOT A, possibly influenced by similar sources and environmental factors. At SPOT C - Dadar Beach, PE emerged as the predominant polymer type, followed by PP and acrylonitrile butadiene styrene (ABS). Nylon and cellulose acetate were also identified, albeit in smaller quantities. This suggests a diverse range of sources contributing to the microplastic pollution in this coastal area. Moving further along the coast to SPOT D - Prabhadevi Beach, a similar trend was observed, with PE being the most prevalent polymer type, followed by PP and PS. PET and EVA were also detected, albeit in smaller proportions. This indicates a comparable composition of microplastics to SPOT A and B, possibly influenced by similar sources and environmental conditions. At SPOT E - Worli Koliwada Jetty, PE emerged as the predominant polymer type, followed by PP and ABS. Nylon and cellulose acetate were also identified, albeit in smaller quantities. This suggests a diverse array of sources contributing to the microplastic pollution in this urban coastal area. Lastly, at SPOT F - Bandra Reclamation, PE was the most prevalent polymer type, followed by ABS and PS. Cellulose acetate and EVA were also identified, albeit in smaller proportions. This indicates a diverse range of sources contributing to the microplastic pollution along this coastal stretch.

Monsoon

Abundance

In monsoon season, the investigation unveiled a slightly elevated mean concentration of MPs, registering at 1080.33 ± 326.79 (Mean ± SD, n=6) per kilogram of dry weight (Fig. 9). The observed increase in MP levels during this period may be attributed to intensified hydrological processes, such as runoff and sediment transport, facilitating the transport and deposition of plastic debris within the bay. The abundance of microplastics varied significantly across the sampled locations, reflecting the diverse environmental conditions and anthropogenic influences present along the Mumbai coastline. At the Opening of Mithi River (SPOT A), the recorded microplastic abundance ranged from 1180 to 1410 items per kilogram of dry weight (items/kg DW), with an average of approximately 1300 items/kg DW. Mahim Beach (SPOT B) exhibited a wider range, spanning from 1280 to 1490 items/kg DW, with an average of 1390 items/kg DW.

Dadar Beach (SPOT C) displayed a narrower range, from 660 to 720 items/kg DW, with an average of around 692 items/kg DW. Prabhadevi Beach (SPOT D) demonstrated a broader range, from 530 to 750 items/kg DW, with an average of 660 items/kg DW. Worli Koliwada Jetty (SPOT E) displayed a range from 1210 to 1460 items/kg DW, with an average of 1328 items/kg DW.

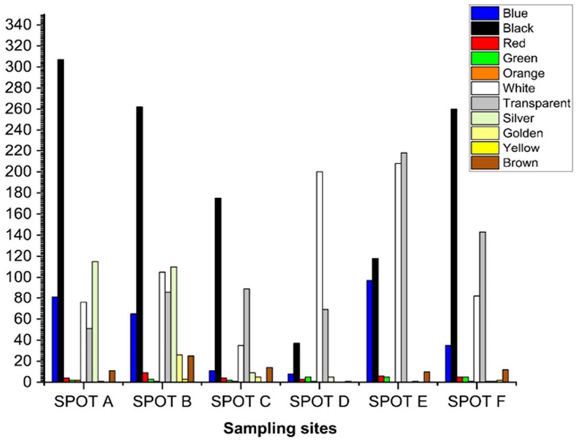

Fig. 4. Color distribution within microplastic pollution across the sampled locations during monsoon

Colour and shape distribution

During the monsoon season, the abundance and color distribution of microplastics exhibited notable variations across the sampled locations along the Mumbai coastline (Fig. 4). At the opening of the Mithi River (SPOT A), the predominant colors observed were black (47.2%), blue (12.46%) and white (11.7%), with smaller proportions of transparent, red, and green microplastics. Mahim Beach (SPOT B) showed a similar trend, with black (37.7%), white (15.1%), and blue (9.35 %) being the most prevalent colors. Dadar Beach (SPOT C) exhibited a different profile, with black (50.6%), transparent 25.72% being the dominant color, followed by white (10.1%) and (8%). Prabhadevi Beach (SPOT D) displayed a diverse range of colors, with white (60.6%) and transparent (20.90%) being prominent, alongside black (11.2%) and blue 2.42% microplastics. Worli Koliwada Jetty (SPOT E) displayed a relatively balanced distribution of colors, with transparent (32.83%), white (31.3%), black (17.8%), blue 14.06% being the primary hues. At Bandra Reclamation (SPOT F), black (46.76%), transparent (25%), white (14.74%), blue 6.29% microplastics were prevalent, while other colors were less abundant.

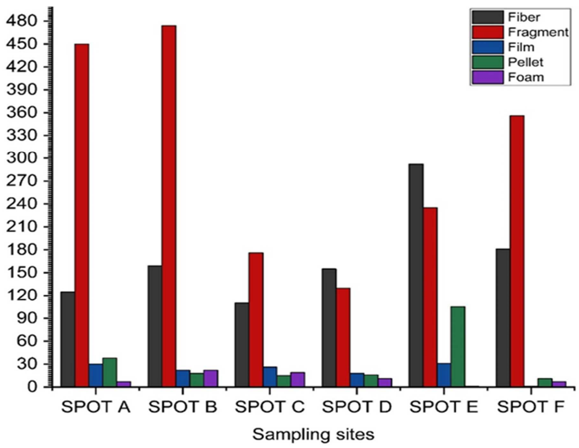

Fig. 5. Shape distribution within the sampled microplastic pollution across various locations during monsoon

The analysis of shape distributions of microplastics across the sampled locations during the monsoon season revealed significant variations in the composition of microplastic shapes (Fig. 5). Fragments were the most prevalent shape category observed across all locations, except SPOT D and SPOT E. At SPOT A - Opening of Mithi River, the predominant shape observed was fragment, constituting a significant 69.23% of the total count, followed by fiber at 19.2%. Film also contributed substantially, representing 4.61% of the observed microplastics. The presence of pellets and foam was relatively minor, making up only 5.85% and 1.08% respectively. This suggests a prevalence of thin plastic films and fibrous materials, possibly originating from packaging or textile sources. In SPOT B - Mahim Beach, a similar trend was observed, with fragment being the most prevalent shape, comprising 68.20% of the total count, followed closely by fiber at 22.29%. Foam also featured prominently, constituting 3.17% of the observed microplastics. The presence of films (3.16%) and pellets (2.59%) was relatively minimal. At SPOT C - Dadar Beach, fragment emerged as the dominant shape, constituting a substantial 50.86 % of the total count, followed by fibers at 31.18 %. Films also contributed significantly, comprising 7.51% of the observed microplastics. Pellets4.34% and foam 5.49% constituted a smaller proportion, further emphasizing the prevalence of broken plastic pieces and thin films along the shoreline. Moving further along the coast to SPOT D - Prabhadevi Beach, a different pattern was observed, with fiber being the predominant shape, constituting 47.00% of the total count, followed closely by fragment at 39.3%. Films also featured prominently, comprising 5.45% of the observed microplastics. Pellets (4.85%) and foam (3.33%) were relatively minor in comparison, indicating a prevalence of degraded plastic fragments and thin films in this coastal environment. At SPOT E - Woli Koliwada Jetty, fibers emerged as the predominant shape, constituting 44% of the total count, followed by fragments at 35.39%. Films also contributed significantly, comprising 4.66% of the observed microplastics. The presence of pellets and foam was relatively minimal, highlighting the prevalence of degraded plastic fragments and thin films in this urban coastal area. Lastly, at SPOT F - Bandra Reclamation, fragment was the most prevalent shape, constituting 64.02% of the total count, followed by fiber at 32.55%. Film also featured prominently, comprising 0.17% of the observed microplastics. Pellets and foam constituted a smaller proportion with percentages of 1.97%, 1.25% respectively, further emphasizing the prevalence of degraded plastic fragments and thin films along this coastal stretch.

Polymer type distribution during monsoon season

The analysis of polymer types present in microplastic pollution during the monsoon season reveals a dynamic composition reflecting the influence of seasonal factors on environmental sources and transport mechanisms (Fig. 8). At SPOT A - Opening of Mithi River, the predominant polymer types observed were polyethylene (PE) and polypropylene (PP), consistent with previous findings. However, nylon and acrylic resin emerged as notable additions during the monsoon, suggesting potential changes in pollutant sources or transport pathways influenced by increased water flow and runoff from upstream areas. In SPOT B - Mahim Beach, a similar trend was observed, with PE and PP being the most prevalent polymer types. Additionally, nylon and acrylic resin were detected, indicating a comparable composition of microplastics during the monsoon season, possibly influenced by similar sources and environmental conditions as observed in other locations. At SPOT C - Dadar Beach, PE and PP remained the predominant polymer types, consistent with observations during other seasons. However, the presence of polyester alongside nylon and acrylic resin during the monsoon suggests a diverse array of sources contributing to microplastic pollution in this coastal area, potentially influenced by changes in riverine inputs and coastal processes. Moving further along the coast to SPOT D - Prabhadevi Beach, a similar pattern was observed, with PE and PP being the most prevalent polymer types. However, the presence of polyester alongside nylon, acrylic resin, and cellulose acetate indicates a diverse range of sources contributing to microplastic pollution during the monsoon season, possibly influenced by changes in coastal dynamics and pollutant transport pathways. At SPOT E - Worli Koliwada Jetty, PE and PP remained the predominant polymer types, consistent with observations during other seasons. However, the presence of PVC alongside nylon and acrylic resin suggests a diverse array of sources contributing to microplastic pollution during the monsoon, possibly influenced by changes in coastal processes and anthropogenic activities. Lastly, at SPOT F - Bandra Reclamation, PE and PP were the most prevalent polymer types, consistent with observations during other seasons. However, the presence of PVC alongside nylon, acrylic resin, and polyester indicates a diverse range of sources contributing to microplastic pollution during the monsoon season, possibly influenced by changes in riverine inputs and coastal dynamics.

Post monsoon

Abundance

In the post-monsoon phase, a notable reduction in MP concentration was discerned, with an average value of 563 ± 198.31 (Mean ± SD, n=6) per kilogram of dry weight (Fig. 9). This decrease in MP abundance following the monsoon season suggests potential alterations in environmental dynamics, such as sediment resuspension and particle settling, influencing the distribution and retention of plastic contaminants within the bay ecosystem. During the post-monsoon season, microplastic abundance was investigated across multiple sampling locations to evaluate the extent of contamination in marine environments. Analysis revealed considerable variability in microplastic levels among the sampled sites. At the opening of Mithi River (SPOT A), microplastic abundance ranged from 330 to 430 items per kilogram of dry weight (DW), with an average of 382.4 items/kg DW. Similarly, Mahim Beach (SPOT B) exhibited a range of 460 to 570 items/kg DW, with an average of 516 items/kg DW. Dadar Beach (SPOT C) displayed a wider range, spanning from 330 to 720 items/kg DW, with an average of 584 items/kg DW. Prabhadevi Beach (SPOT D) showcased notable variations, with microplastic abundance ranging from 530 to 840 items/kg DW and an average of 689.6 items/kg DW. Woli Koliwada Jetty (SPOT E) demonstrated a range of 560 to 720 items/kg DW, averaging at 635.6 items/kg DW. Conversely, Bandra Reclamation (SPOT F) depicted lower microplastic levels, ranging from 180 to 390 items/kg DW, with an average of 308.8 items/kg DW.

Colour and shape distribution

At the opening of Mithi River, blue-colored microplastics comprised approximately 19.14% of the total sampled items, while black microplastics were the most prevalent at 40.96%. White-colored microplastics constituted 20.21% of the samples, with transparent microplastics following closely at 7.44%. Notably, red-colored microplastics were also present, representing 5.3% of the samples. Additionally, a small percentage of silver-colored microplastics (1.04%) and brown -colored microplastics (3.72%) were observed, along with traces of green 2.12%. However, silver-colored microplastics were minimal in this location. Moving to Mahim Beach, black and blue microplastics were prominent, comprising approximately 49.02% and 16.01% of the total samples, respectively. White -colored microplastics were also notable at 14.45%, along with transparent microplastics, which accounted for 9.37% as well. No pink-colored microplastics were recorded in the Mahim Beach samples. At Dadar Beach, black-colored microplastics dominated the samples, making up 45.48% of the total. White-colored microplastics were also prevalent at 22.06%, while transparent-colored microplastics constituted 14.25% of the samples. A small percentage of blue and red -colored microplastics (4.51% and 4.23) respectively were observed, along with traces of brown, golden, and silver microplastics.

Prabhadevi Beach exhibited a diverse range of microplastics colors, with black microplastics being the most prevalent at 62.56%, transparent and white microplastics followed at 22.41% and 5.66 %, respectively. Additionally, blue-colored microplastics were notable at 4.43%, while red-colored microplastics constituted 2.21% of the samples. Other colors such as yellow, brown, and red were also present but in smaller quantities. Pink-colored microplastics were scarce in this location. Worli Koliwada Jetty presented a varied distribution of microplastics colors, with black microplastics being the most prevalent at 31.29%. Transparent and White microplastics were also notable, comprising 22.58% and 20.32% of the total samples, respectively. Other colors like blue, red, and orange were present but in smaller percentages. Additionally, orange -colored microplastics were minimal, making up only 0.64% of the samples. Lastly, Bandra Reclamation exhibited a significant presence of black and transparent microplastics, constituting 34.78% and 33.54% respectively. White microplastics followed at 21.74%, while blue and brown microplastics were notable at 4.96% and 1.86%, respectively. Green and pink colored microplastics were also present at 0.62%. Other colors such as yellow, brown, and red were observed but in smaller quantities. Similarly, pink-colored microplastics were minimal in this location (Fig. 6).

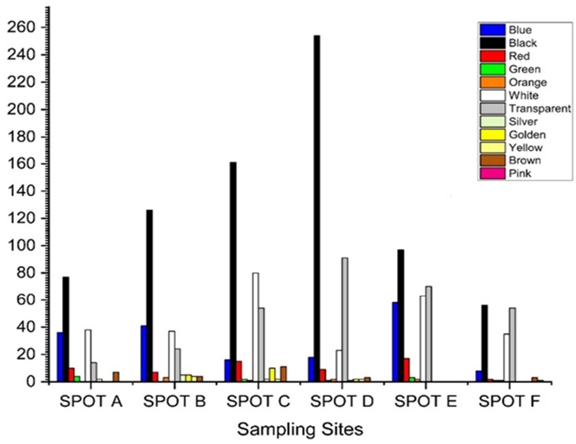

Fig. 6. Color distribution within microplastic pollution across the sampled locations during post-monsoon

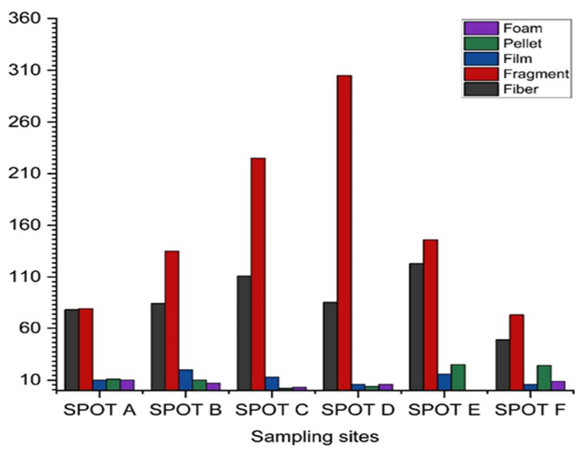

Fig. 7. Shape distribution within the sampled microplastic pollution across various locations during post-monsoon

Microplastic shape distribution analysis conducted at various locations presents insightful findings (Fig. 7).

At the Opening of Mithi River post-monsoon, fragment and fiber -shaped particles dominate, constituting around 42.02 and 41.49% of the total abundance, while pellet particles account for approximately 5.85%. Films, and foam collectively contribute to the remaining microplastic abundance, with films and pellets at 5.31%, each. Similarly, at Mahim Beach, Dadar Beach, Prabhadevi Beach, and Worli Koliwada Jetty, fragment -shaped microplastics prevail at approximately 63.55%, 75.12%, 47.09% and 45.34% respectively followed by fiber shapes for these locations as 31.04%, 20.9%, 39.07%and 30.4%. Films, pellets, and foam collectively contribute to the rest of the microplastic distribution.

Polymer type distribution post-monsoon

The examination of polymer types presents in the sampled microplastic pollution post-monsoon period across various locations reveals distinct variations in composition, reflecting changes in environmental conditions and pollutant sources (Fig. 8). At SPOT A - Opening of Mithi River, polyethylene (PE) emerged as the predominant polymer type, followed by polypropylene (PP) and polystyrene (PS). Nylon and cellulose acetate were also identified, albeit in smaller proportions. This suggests a continued presence of diverse plastic materials, potentially influenced by runoff from urban areas and industrial activities during the monsoon season.

Moving to SPOT B - Mahim Beach, a similar trend was observed, with PE being the most prevalent polymer type, followed by PP and PS. Nylon and cellulose acetate were also detected, alongside the emergence of ethylene-vinyl acetate (EVA) and polyethylene terephthalate (PET).

This indicates a shift in polymer composition post-monsoon, possibly due to the introduction of new plastic materials from various sources, including marine debris and coastal activities. At SPOT C - Dadar Beach, PE remained the predominant polymer type, followed by PP and PS.

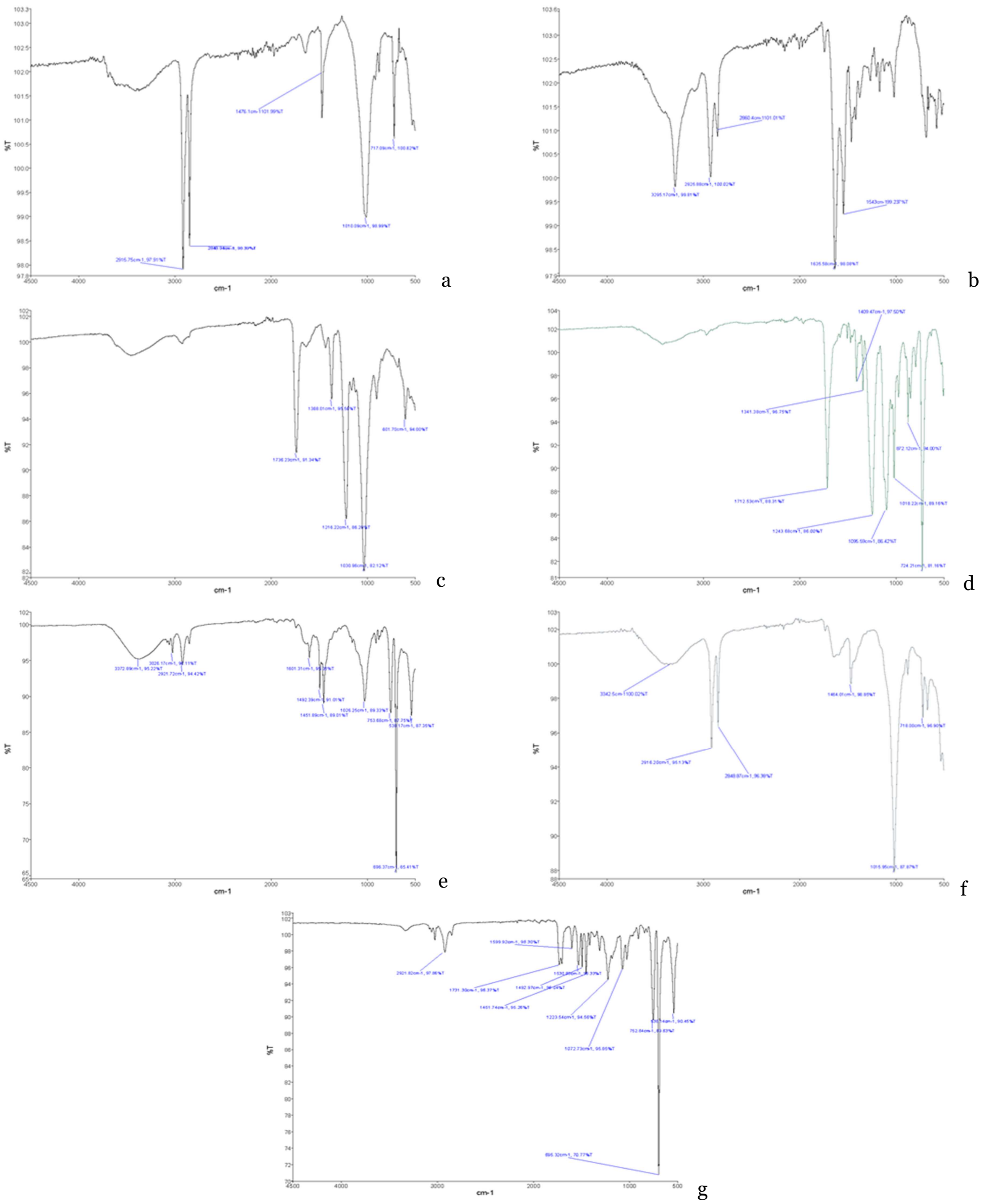

Fig. 8. FTIR spectra of microplastic samples: a. PE (Polyethylene), b. Nylon, c. CA (Cellulose Acetate), d. PET (Polyethylene Terephthalate), e. Pellet, f. EVA (Ethylene Vinyl Acetate), g. ABS (Acrylonitrile Butadiene Styrene)

Nylon and cellulose acetate were also identified, along with the emergence of EVA and PET.

This suggests a continuation of plastic pollution from diverse sources, with potential contributions from both land-based and marine activities. Moving further along the coast to SPOT D - Prabhadevi Beach, a similar pattern was observed, with PE being the most prevalent polymer type, followed by PP and PS. Nylon and cellulose acetate were also detected, alongside the emergence of EVA and PET. This indicates a comparable composition of microplastics to other locations, possibly influenced by similar sources and environmental conditions. At SPOT E -

Worli Koliwada Jetty, PE remained the predominant polymer type, followed by PP and PS.

Nylon and cellulose acetate were also identified, alongside the emergence of EVA and PET. This suggests a continued presence of diverse plastic materials, potentially influenced by both land-based and marine sources. Lastly, at SPOT F - Bandra Reclamation, PE was the most prevalent polymer type, followed by PP and PS. Nylon and cellulose acetate were also identified, alongside the emergence of EVA and PET. This indicates a diverse array of plastic materials present post-monsoon, reflecting the complex nature of microplastic pollution along this coastal stretch. These findings underscore the dynamic nature of microplastic pollution in coastal environments and highlight the importance of continued monitoring and mitigation efforts to address this pervasive environmental issue.

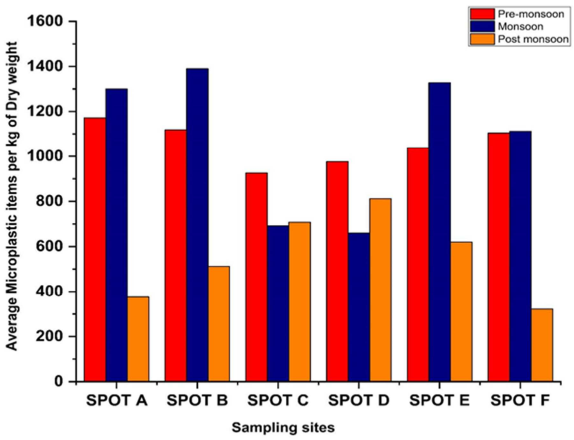

Fig. 9. Average microplastics items per kilogram of dry weight across three seasons

Microplastic pollution has become a pressing environmental concern globally, with coastal regions being particularly vulnerable to its adverse effects. The present study focused on evaluating the abundance, color distribution, shape distribution, and polymer type distribution of microplastics in Mahim Bay across different seasonal periods. The findings shed light on the extent and characteristics of microplastic pollution in this semi-enclosed segment of the Arabian Sea, providing valuable insights for understanding and addressing this environmental challenge. During the pre-monsoon season, the average concentration of microplastics was found to be 1055.66 grams per kilogram of dry weight (items /kg DW). This value is comparable to findings from similar studies conducted in coastal areas worldwide. For instance, a study by reported microplastic concentrations ranging from 500 to 1500 particles per kilogram of sediment in the intertidal zones of coastal regions in the Sishili Bay, North Yellow Sea, China (Zhang *et al.,* 2019). Likewise, another research effort recorded levels of microplastic varying between 800 to 1200 particles per kilogram of sediment along the coastline of the German Baltic Sea (Stolte *et al.,* 2015). The findings of our study align with these previous observations, indicating the widespread distribution of microplastics in coastal sediments. In contrast, the monsoon season exhibited a slightly elevated mean concentration of microplastics, registering at 1080.33 g/kg DW. This increase may be attributed to intensified hydrological processes such as runoff and sediment transport during the rainy season, facilitating the transport and deposition of plastic debris within the bay. Similar seasonal variations in microplastic abundance have been reported in other studies. For example, a study observed higher microplastic concentrations in surface waters during the wet season compared to the dry season in the Pearl River Estuary (Han *et al.,* 2020). The findings of our study corroborate these observations, highlighting the influence of seasonal factors on microplastic distribution in coastal environments. In the post-monsoon phase, a notable reduction in microplastic concentration was discerned, with an average value of 563 items /kg DW. This decrease suggests potential alterations in environmental dynamics, such as sediment resuspension and particle settling, influencing the distribution and retention of plastic contaminants within the bay ecosystem. Similar post-monsoon reductions in microplastic abundance have been reported in other studies. For instance, a study documented a decrease in microplastic concentrations in sediments following the wet season in estuarine sediments from urban canal on the west coast of Thailand (Jiwarungrueangkul *et al.,* 2021).

The findings of our study align with these observations, indicating the seasonal variability of microplastic pollution in coastal environments.

The examination of color distribution within microplastic pollution across the sampled locations revealed noteworthy disparities, with each locale presenting distinct compositions in terms of color categories. Black and white microplastics were prevalent across all seasons, indicative of common plastic types such as polyethylene and polypropylene. However, variations in color distribution were observed, reflecting differences in pollution sources and environmental conditions among the sampled locations. Similarly, the analysis of shape distribution within microplastic pollution unveiled distinctive patterns and proportions, highlighting the diverse composition of pollutants present in each environment. Fiber-shaped microplastics were consistently dominant across all seasons and locations, followed by fragmented particles (Fig. 10). This suggests a prevalence of fibrous materials and degraded plastic fragments in the marine environment, possibly originating from sources such as textiles and packaging materials (Lambert *et al.,* 2013).

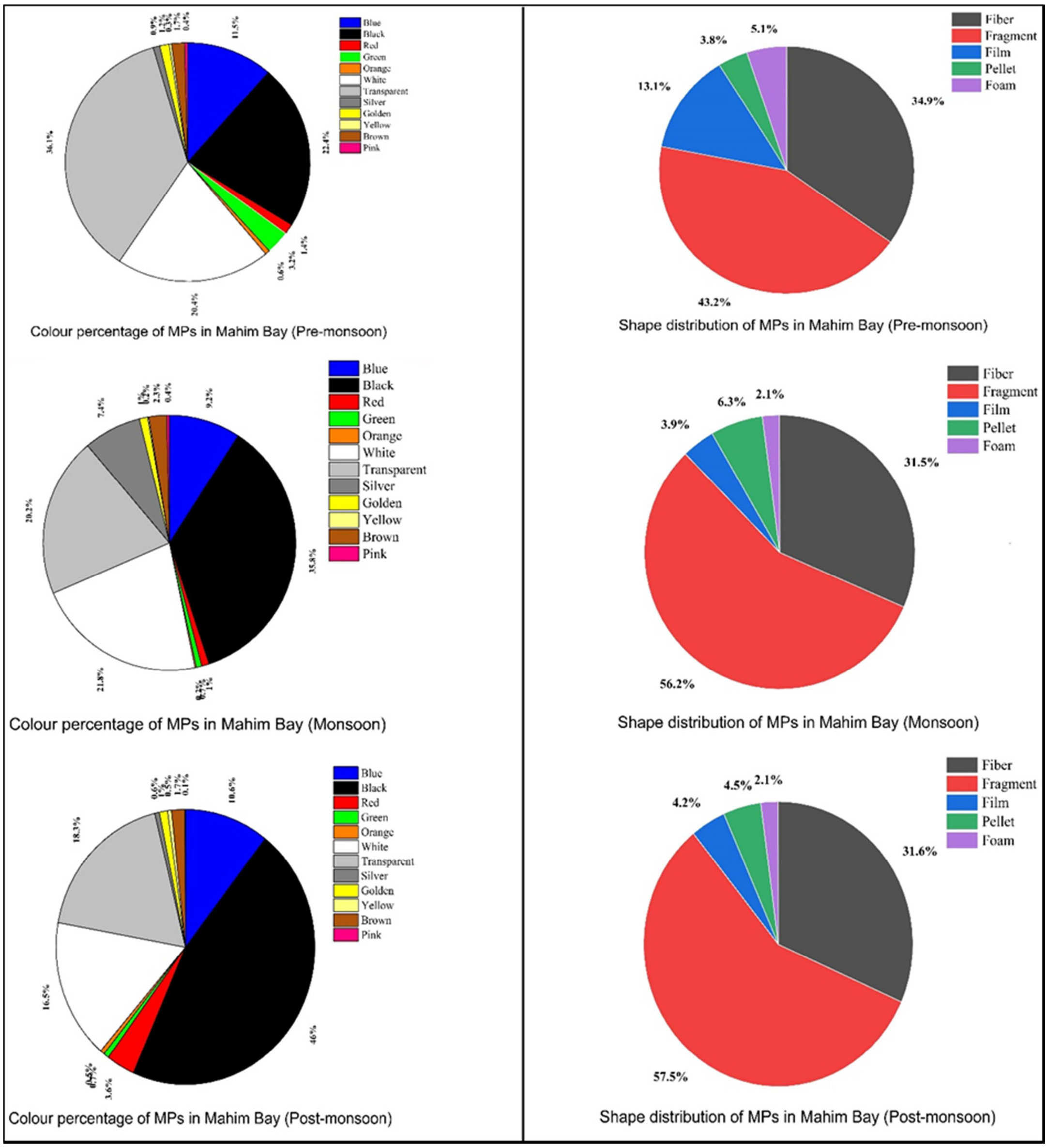

Fig. 10. Colour and shape distribution of MPs in Mahim Bay across three seasons

An examination of the polymer types presents in microplastic pollution revealed a dynamic composition reflecting the influence of seasonal factors on environmental sources and transport mechanisms. Polyethylene (PE) and polypropylene (PP) were the most prevalent polymer types across all seasons and locations, consistent with common plastic materials used in packaging and consumer products. However, variations in polymer composition were observed, indicating differences in pollution sources and transport pathways among the sampled locations. Comparing our findings with previous studies, similar patterns of polymer type distribution have been reported in coastal environments worldwide. A study by GESAMP (2019) documented PE and PP as the predominant polymer types in marine microplastics, accounting for over 50% of the total polymer composition (GESAMP, 2019). Additionally, studies reported PE and PP as the most abundant polymer types in coastal sediments and surface waters (Li *et al.,* 2021; Reinold *et al.,* 2021; Takarin *et al.,* 2022). The consistency of these findings suggests common sources and pathways of microplastic pollution in coastal environments globally (Ajith *et al.,* 2020; Koutnik *et al.,* 2021).

In this study, Fourier-transform infrared spectroscopy (FTIR) was employed to analyze the chemical composition of microplastic particles extracted from sediment samples collected in Mahim Bay, Mumbai. FTIR spectroscopy provides valuable insights into the molecular structure and composition of microplastics, aiding in the identification of polymer types present in the samples. Observed peak values corresponding to characteristic functional groups of different polymers were analyzed to determine the polymer composition of the microplastic particles.

Commonly observed peaks included those indicative of polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), among others. These peak values were compared with reference spectra to confirm the presence of specific polymer types, providing crucial information for understanding the sources and pathways of microplastic pollution in Mahim Bay (Fig. 8).

Conclusion

In conclusion, our study provides comprehensive insights into the distribution and dynamics of microplastic pollution in Mahim Bay across different seasonal periods. The analysis revealed varying concentrations of microplastics during the pre-monsoon, monsoon, and post-monsoon seasons, highlighting the influence of seasonal factors on plastic pollution dynamics in coastal environments. During the pre-monsoon season, elevated microplastic concentrations were observed, indicating the pervasive presence of plastic debris in sediments. The monsoon season exhibited slightly higher microplastic levels, attributed to intensified hydrological processes such as runoff and sediment transport. In contrast, the post-monsoon phase showed a notable reduction in microplastic abundance, reflecting changes in environmental dynamics such as sediment resuspension and particle settling. Our findings underscore the importance of considering seasonal variations in microplastic pollution when assessing the impact of plastic debris on marine ecosystems. The observed fluctuations in microplastic abundance highlight the dynamic nature of plastic pollution in coastal environments and emphasize the need for long-term monitoring to understand temporal trends and drivers of plastic pollution. Moreover, our study contributes to the growing body of knowledge on microplastic pollution in semi-enclosed marine environments, such as Mahim Bay, and underscores the importance of targeted management and conservation efforts to mitigate the impact of plastic pollution on marine ecosystems and human health. Overall, our findings emphasize the urgent need for effective strategies to reduce plastic pollution at its source and mitigate its adverse effects on marine environments. By understanding the seasonal variations and drivers of microplastic pollution, policymakers, researchers, and stakeholders can develop evidence-based interventions to address this pressing environmental issue and safeguard the health and integrity of coastal ecosystems for future generations.

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