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# Spatial and seasonal variations in abundance, distribution characteristics, and sources of microplastics in surface water of Mula river in Pune, India ☆

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ABSTRACT

Microplastics are one class of widely prevalent emerging contaminants that have a detrimental effect on ecosystems and human health. The status of microplastic pollution in rivers in Western India is not well documented, making it difficult for establishing monitoring policies and guidelines. Mula river in Pune is a lifeline for the numerous industries and residential establishments in the city and hence monitoring the health of the water of Mula river is of great societal relevance. This investigation elucidated the prevalence, abundance and characterization of microplastics in Mula River water, while it crosses Pune, one of the fastest developing cities in India. Season played a determinant role in microplastic abundance. During the pre-monsoon season, the average microplastic concentration at all the three selected locations was notably higher (1808 ± 697 particles/L) compared to the post-monsoon period (1561 ± 167 particles/L). Microplastics smaller than 100 μm were consistently dominant in both the seasons. Notably, the most common polymer found in the Mula River was Ethylene Vinyl Acetate (EVA), a copolymer of polyethylene (PE) and vinyl acetate, commonly used in plastic wraps and packaging material. Unregulated disposal of industrial waste emerged as the most potential source of microplastics in Mula river. This study addresses a critical knowledge gap about the distribution and sources of microplastics in rivers in India. This work provides baseline data that can be used to access accurate mitigation of microplastics and evaluate health and environmental impacts of microplastic pollution in Indian rivers.

## 1. Introduction

Pollution of environmental niches due to various emerging contaminants of concern is a grave ecological and human health hazard. Plastic polymers have emerged as one of the most widespread pollutants across all ecosystems and life forms. Indiscriminate and unsolicited discard of plastic waste is the prime reason for the widespread presence of these pollutants in environmental niches. As per a report by the United Nations Environmental Protection (UNEP), around 19–23 million tonnes of plastic waste, finds its way into aquatic environments, including lakes, rivers, and oceans, each year (UNEP, 2024). Plastic pollution can alter natural processes and habitats, making it difficult for ecosystems to adapt to climate change. This directly impacts the social and economic well-being of millions of people and their ability to sustain under changing climatic conditions. National Oceanic and Atmospheric Administration (NOAA) characterizes microplastics (MPs) by their small size (<5 mm), light weight, and resistance to degradation, allowing them attributes to persist in the water environment for extended periods (NOAA, 2023). Freshwater ecosystems are at increasing risk from microplastic pollution due to the ability of microplastics to adsorb organic matter, heavy metals, and other toxic substances (Nath et al., 2023). Furthermore, it has also been reported that MPs adsorb radioactive substances on their surface, increasing their retention time in aqueous environment for longer durations (Ikenoue et al., 2022). Microplastics offer a wide and conducive surface for the attachment of microorganisms, increasing microbial interactions, accelerating biofilm formation, facilitating horizontal gene transfer and thereby promoting the expansion and spread of the antimicrobial-resistant pathogen population (Nath et al., 2023). Additionally, subsequent release of additives from various plastic polymers increases their toxicity potential (Qian et al., 2023). This further amplifies the negative impacts of microplastics, making them a potential public health and ecological hazard.

There are multiple reports covering the abundance and distribution of MPs in various environmental niches, including wastewater treatment

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plants (Bayo et al., 2020), sewage (Patil et al., 2023), landfills (Verma et al., 2024; Shen et al., 2022), and river water and sediment. Rivers are a key source of fresh water but act as a temporary sink of various anthropogenic pollutants, including microplastics. Multiple studies on microplastic abundance in river water are being undertaken globally. Microplastics in the range of 0–230 pieces/m$^3$ were reported from Wu River, Taichung City in Taiwan (Kunz et al., 2023). Quantification of MPs in the surface water of Yellow River, China, revealed particles in the range of 2511 $\pm$ 2971.27 n/L and 432.5 $\pm$ 240.54 n/L, in wet and dry season respectively (Qian et al., 2023). Microplastics abundance in freshwater sediments of the St. Lawrence River, Canada, was found to be 832 $\pm$ 150 plastics/kg (Crew et al., 2020). India is a developing country with increasing industrialization, urbanization and expanding population. There has been a rise in the number of published reports on microplastic distribution in few of the major river systems in India. However, majority of the studies are focused on microplastic distribution in river sediments, with limited work done on surface water of rivers intended for domestic use. Few reports on MPs from river sediments include 134.53 mg/kg (75–212 μm) and 581.706 mg/kg (212–4 mm) from Sabarmati river sediment (Patel et al., 2020), 258.7 $\pm$ 90.0 particles/kg in Odisha beach sediment (Patchaiyappan et al., 2021), 5, 76,000–1,000,000 particle/kg in sediments from upstream to downstream of River Ganga (Singh et al., 2022a, 2022b; Gupta et al., 2024), 180 $\pm$ 13.44 particles/kg in soil from Bhopal (Singh et al., 2023), and 500–3900 MP/m$^3$ in River Yamuna (Vaid et al., 2022). Reports on MPs in the surface waters of rivers in Southern and Western India are scanty and require further research.

Considering the criticality of the global microplastic pollution crisis, and the need to build clean and healthy freshwater resources, this study aimed to quantify and characterize the distribution of microplastics in the surface water samples of the Mula River, Pune, Maharashtra, India. According to the census 2011, the population of the state of Maharashtra in Western India was 112.492 million, accounting for 9.29 percent of the total population of the country. Mumbai and Pune are the two largest populated cities in Maharashtra (Economic Survey, 2011). Pune is one of the fastest developing and expanding cities in India, with multiple universities, and a wide variety of automobile and manufacturing industries centred in and around the city. Mula river is regarded as the lifeline of Pune city with the waters of Mula River being utilized for farming, industrial work, household chores, drinking and bathing. However, the growing population and expanding urban and industrial activities with inadequate infrastructural support and waste management has greatly impacted the quality of river water, exacerbating the water crisis in the city. Pollution of river water due to excessive disposal of domestic and industrial solid waste and untreated wastewater has led to severe deterioration in the water quality (MPCB, 2018).

This work aims to study the abundance, distribution and seasonal variation in microplastics present in surface water of Mula river, Pune city, and assess the contribution of Pune city in the MP load of the water. There are currently no reports on microplastic pollution in Mula river water in Pune city. Studying the distribution of MPs in the surface waters of Mula river will aid in understanding the hazards associated with water use, assist in identifying probable sources, and help stakeholders make informed interventions for improving and maintaining freshwater quality. The data generated from this study will be helpful in devising pollution mitigation and effective waste management strategies to address the local challenges. The data obtained will be shared with the water quality monitoring authorities in the Government to highlight the problem of contamination of water with microplastics. Identifying probable causes will help develop targeted interventions to curtail MP pollution in river water.

## 2. Materials and methods

### 2.1. Study area

In this study, Pune city, situated in the state of Maharashtra in western India, was considered. Pune (180 31′ N, 82,730 51′ E) is located 560 m above mean sea level (MSL) on the western margin of the Deccan Plateau. Mula river covers a distance of over 52 km from Mulshi dam to its union with Mutha river in Pune city. For about 40 km, the river passes through hilly regions of villages, Paud, Nande and Chande, each with population of less than 10,000. Subsequently river Mula transverse through the heart of Pune city covering a distance of 22.2 km within Pune municipal corporation limits, passing through densely populated regions with widely established industrial units and scattered agricultural fields. As a result, industrial waste, household garbage, hospital and industrial effluents, and some agrarian run-offs, intentionally or unintentionally, find their ways into Mula river (MPCB, 2018). The 22.2 km stretch of Mula river entering the Pune metropolitan area near Wakad, and traversing through Aundh and Bopodi, until its union with river Mutha in the centre of the city, was selected as the area of study. All the three sampling points, Wakad, Aundh and Bopodi, fall within the stretch of the river in city limits (Kshirsagar and Gunale, 2011).

### 2.2. Water sample collection and pretreatment

On the basis of anthropogenic activities, sampling from some selected area on Mula river was done from three locations, Wakad (L1), Aundh (L2) and Bopodi (L3) (Fig. 1).

Samples were collected in two seasons, before the onset of monsoon season and after the end of monsoon season in Pune, India. Random sampling methodology was followed for the sampling. Water samples were collected pre and post monsoon to understand the seasonal distribution, as the MP generation and distribution is dependent on environmental factors. The pre-monsoon sampling was done in the dry summer month of March, which is marked by high temperatures (37–45 °C) in the area, while post-monsoon sampling was done in the month of November, when the day temperatures is around 25–30 °C. Sampling was done during dry days with no rain for a minimum of 6–7 days. From each location, 10 L water sample was collected in polytetrafluoroethylene (PTFE) bottles from a depth of 0.5 m below the surface without disturbing the waterbed or sediment at the river banks. Water sample collected from each location was analysed in triplicates. Details of the locations selected for the study are given in Table 1.

All the samples were primarily sieved by a 5 mm stainless steel sieve at the sampling site to ensure filtering out, and exclusion, of particles of size > 5 mm. The samples thus collected, were stored in glass bottles at 4 °C for further analysis.

### 2.3. Water sample processing

Processing of water samples for the study of microplastics was done using the method described by the National Oceanic and Atmospheric Administration (NOAA, 2015) with slight modifications. The stored water samples were prefiltered using 1 mm stainless-steel filters to separate and collect microplastics >1 mm size. Chemical digestion method, followed by density separation, was employed for the digestion of organic matter and separation of MPs respectively (Sekar and Sundaram, 2023). Filtered water samples were digested using Fenton's reagent in a ratio of 2:1 (30 % $H_2O_2$: Fe II). The mixture was heated at 75$^o$ C with constant stirring at 1000 rpm for 30 min. After cooling, 32 g NaCl was added to the sample and stirred for another 30 min. Samples were subsequently left undisturbed for 24 h. The mixtures were again filtered using cellulose filters of different pore sizes: 25 μm, 11 μm and 2 μm. Finally, the filter papers containing MPs were washed with distilled water, dried and stored in glass containers. Clean ultrapure water was used as a control. As per the protocol followed for extraction of MPs, it

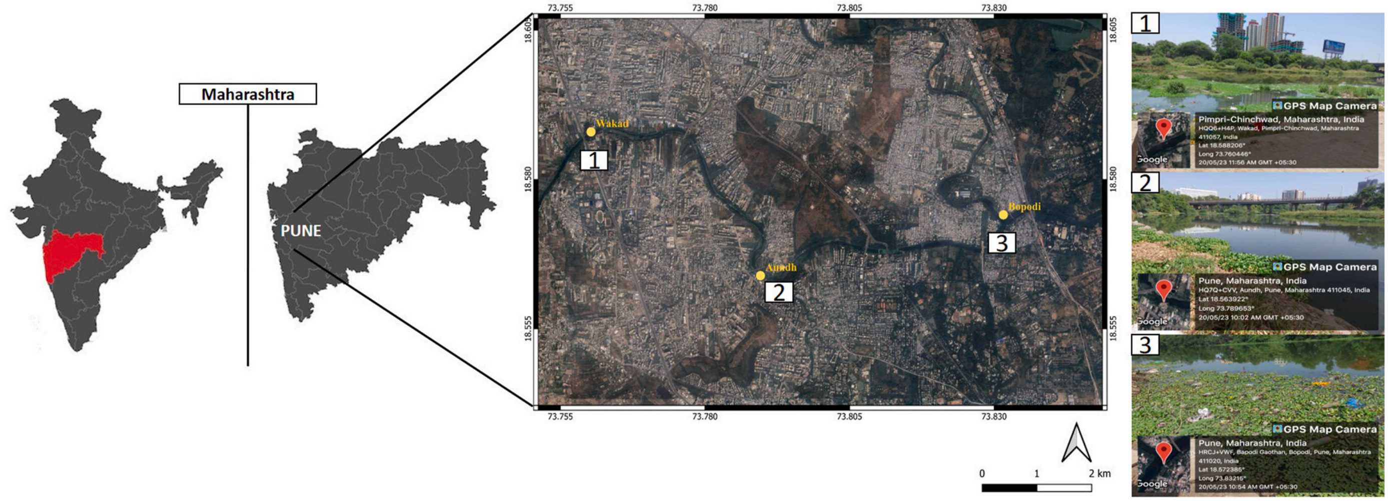


**Fig. 1.** Quantum Geographic Information System (QGIS) mapping of sampling sites for Mula river.

**Table 1**
Details of the locations and sampling sites.

| Location name (codes) | Latitude, Longitude | Elevation over MSL (m) | Population (Economic Survey, 2011) | Pre-monsoon samples | Post-monsoon samples |
|---|---|---|---|---|---|
| Wakad (L1) | 18.5881°, 73.7603° | 570 | 31972 | 1 (10L × 3) | 1 (10L × 3) |
| Aundh (L2) | 18.5638°, 73.7896° | 565 | 17766 | 1 (10L × 3) | 1 (10L × 3) |
| Bopodi (L3) | 18.5741°, 73.8322° | 560 | 15843 | 1 (10L × 3) | 1 (10L × 3) |

Source: (https://pmc.gov.in/); (https://gpsmapcamera.com/)

was assumed that after the digestion of organic particles, the recovered particles on filter papers were MPs, which were then further analysed.

### 2.4. Microplastics analysis

Microplastics collected on different-sized filter papers were visually observed under optical microscope (Olympus BX53) with suitable magnification (10× to 40X) and expressed as particles/L (Rajan et al., 2023). Cell Sens Entry image software was used for the visual analysis. Microplastics were classified based on various physical properties including shape, color and size. Based on shape, MPs were documented as fragment (sharp items, rods), foam (fuzzy items), film (thin sheet items), fiber (long thread items) and microbeads (round items). Based on color, MPs were diversified as black, white/transparent, grey, red, blue or yellow. Based on microscopic observations, MPs were divided into five size groups 25–100 μm, 101–500 μm, 501–1000 μm, >1–2 mm and >2–5 mm.

### 2.5. Polymer identification

The chemical characterization of the segregated representative MPs from all locations, and across both seasons, was done using Attenuated Total Reflectance (ATR) attached Fourier Transform Infrared Spectroscopy (FTIR) (BRUKER ALPHA II) at the Central Instrumentation Facility, of Savitribai Phule Pune University, Pune, India. Around 10 scans at a scan speed of 0.20 cm/s were taken to produce the spectra with wavelengths between 600 and 4000 $cm^{-1}$ and with the spectral resolution of 4 $cm^{-1}$. OpenSpecy software was also employed for the confirmation of the spectra. Spectra with Pearson's value (r > 90) was considered for analysis. Though, based on microscopic examinations, the particle size range was defined, all the particles of different size ranges could not be processed for polymer composition owing to difficulty in collection and handling of particles below 1 mm size. In addition, owing to the limitations in placing particles of less than 1 mm size under the available FTIR equipment with naked eyes, the representative MP particles of the size range 2–5 mm were chosen for FTIR analysis.

### 2.6. Quality control

All instruments and glassware used in the study were carefully rinsed with ultrapure water during the experiment to avoid potential airborne plastic contamination in the sample. Ultrapure water was used as a control. Similar to the test samples, ultrapure water (100 ml) was subjected to 10 ml of Fenton's reagent for digestion and sodium chloride density separation for microplastics extraction (section 2.3). Although digestion protocols were not conducted in controlled-airflow areas, for example laminar flow hood or fume hood, throughout the experiment samples were covered with glass plates or aluminium foil to avoid air contamination. Sterile, and clean knee length laboratory coat and nitrile gloves were worn to limit microfiber contamination (Prata et al., 2021). Work surfaces were regularly wiped with distilled water and 70 % ethanol. Only glass and metal tools were used for handling microplastics. Microplastics in the control were confirmed to be less than 5 % of experimental groups, thereby confirming the exclusion of any traces of background pollution in the study.

### 2.7. Statistical analysis

A two-way factorial ANOVA was conducted using IBM SPSS Statistics (v. 24.0) to investigate the influence of location (Wakad, Aundh, Bopodi) and season (pre-monsoon, post-monsoon) on the response variable of microplastic prevalence in the Mula River. This 3 × 2 factorial design examined the interaction between these two factors, with three replicates per interaction subgroup. The assumptions of general linear model (GLM) were supported due to availability of reasonable sample size providing fairly good degrees of freedom for statistical tests. Shape, colour, and size, being interdependent characteristics of individual microplastic particles, were not included as independent factors in the factorial model to avoid violating independence assumptions. Microplastic prevalence was analysed, and associated *p*-values were reported. Statistical significance was determined at $\alpha = 0.05$*. We reported only those significance tests which were either significant or just non-significant. Ryan-Einot-Gabriel-Welsch studentised Range tests were conducted as a post-hoc analysis to identify homogenous groups after the main effects were found significant. The evidence of main, simple and interaction effects, hence form an important part of discussions.

## 3. Results and discussion

Varying number and types of microplastics were observed in Mula river surface water during different seasons and at different locations in the Pune city. The overall $3 \times 2$ factorial model (predicting Microplastic = Intercept + Location + Season + Location × Season) was statistically significant ($p = 0.001$, $\eta^2 = 0.846$, power = 0.99, $R^2_{adj} = 0.782$). Notably, the GLM included essential 2-way interaction between Location and Season. We got encouraging results that often-followed scientific logic.

### 3.1. Prevalence and abundance of microplastics

Tables 2 and 3 present the descriptive and statistical analyses based on the data of water samples collected at the three locations and two seasons. For the ease of reading, we presented mean microplastic (and SD) and 95 % CI values in integer form.

The microplastic prevalence across all locations was notably high (95 % CI exceeds null value), among which a significant minimum microplastic prevalence was observed at Aundh during pre-monsoon (95 % CI (682, 1278). The number of microplastics in the surface water (at 0.5 m depth) at Wakad before monsoon was highest (2413 ± 445 particles/L), while Aundh location gave the lowest microplastics count (980 ± 182 particles/L). At Aundh, microplastic prevalence during post-monsoon was significantly higher than during pre-monsoon ($p = 0.002$). At Bopodi, the difference between pre-monsoon and post-monsoon microplastic prevalence was significant ($p = 0.010$). At Wakad, microplastic prevalence during pre-monsoon was significantly higher than during post-monsoon ($p = 0.001$). A statistically significant interaction effect between location and season was also observed ($p = 0.001$, Power = 0.99). Pairwise comparisons revealed just significant difference in microplastic prevalence between Aundh and Bopodi ($p = 0.049$), but the difference between Aundh and Wakad approached significance ($p = 0.002$) (Table 3).

Post-hoc analysis using the Ryan-Einot-Gabriel-Welsch (REGWQ) test identified Bopodi and Wakad ($p = 0.105$), a homogeneous group of microplastic prevalence, different from Aundh. Microplastic prevalence was highest (95 % CI (1635, 1980)) during pre-monsoon than in post-monsoon (95 % CI (1389, 1733)). While pre-monsoon prevalence was numerically higher, the difference between seasons nearly approached statistical significance ($p = 0.048$). This was also confirmed by non-significant independent pairwise comparisons between the number of microplastics of the season factor ($p = 0.048$) (Table 3). During pre-monsoon, microplastic prevalence at Bopodi was significantly higher than at Aundh ($p = 0.001$), and prevalence at Wakad was also significantly higher than at Aundh ($p = 0.001$). During post-monsoon, however, pairwise comparisons among locations were not significant ($p > 0.05$). Parameter estimates, significance of the estimated factorial model and quality criteria are detailed in Supplementary Table 1.

As evident from Tables 2 and 3, there is a significant shift in microplastic abundance post-monsoon season, and a decrease in microplastic count at two of the locations studied, reiterating that monthly river plastic inputs into the ocean are affected by increased rainfall linked to monsoon. This variation may be due to rainfall conditions, increased flow intensity of the river, such as flood or high intensity water release from dams, as is prevalent during the monsoon season, land topography, and elevation of the river at the sampling point. Similar findings were observed in a few earlier studies as mentioned in Table 4.

Spatial differences in the amount of microplastics in river water determine the relationship between microplastics abundance and seasonal variation (Kunz et al., 2023). Microplastics are suspended loads, and their geographical distribution is determined by multiple factors, including river barriers, discharge, confluences, bed morphology, and water depth. Based on the awareness, literacy and behavioural change levels, waste collection, processing and the overall management mechanisms and strategies adapted, the areas with the lowest relative population densities may tend to have the higher microplastics levels, while certain locations in the densest areas may give lower microplastics abundance. Additionally, the size of the study locations and population density also affects microplastic abundance. Samples collected from areas with extreme population densities or at coarse distances can exhibit stronger correlations than samples from the same catchment collected on a smaller scale (Kumar et al., 2021).

Wakad (L1), with a population density of 3449/km$^2$ and an area of approximately 9.49 km$^2$, is located close to a populated industrial area with chemical, manufacturing and automobile industries situated along the river. Wakad is also known as a transportation hub and is located along a busy vehicular corridor, the Mumbai-Pune-Bangalore highway. The location of the sampling site Wakad (L1) close to a populated industrial area and a busy road could be a reason for the high number of microplastics recorded at this location. Least number of microplastics were recorded at Aundh (L2) location which is primarily a residential area. Educated, environmentally aware urban population residing in the Aundh area can be engaged in better segregation and controlled disposal of waste in the region leading to reduced waste dumping in the Mula river. However, an increase in the load of MPs at Aundh (L2) after monsoon season can be attributed to increased runoffs into river water from surrounding areas, and river elevation facilitating the accumulation of MPs. Reports on microplastics in rivers in Western India are limited. In a recent study, 3.9 items/L of MP from the Godavari River in Andhra Pradesh, India has been reported (SekarSundaram). The load of microplastics in river water in the current study, was multiple folds higher than the study of Godavari river water, implying a heightened need to address the issue of microplastic pollution in other rivers of Western India.

**Table 2**
Significance of microplastics (MP) at Location, Season and their combinations.

| Factor levels/ Combinations | Microplastic measurements | Mean MP[a] ± SD | SE | 95 % CI for MP |
|---|---|---|---|---|
| Aundh | 6 | 1350 ± 426 | 96.9 | (1139, 1561) |
| Bopodi | 6 | 1732 ± 364 | 96.9 | (1521, 1943) |
| Wakad | 6 | 1972 ± 572 | 96.9 | (1761, 2183) |
| Pre-monsoon | 9 | 1808 ± 697 | 79.1 | (1635, 1980) |
| Post-monsoon | 9 | 1561 ± 167 | 79.1 | (1389, 1733) |
| Aundh & Pre-monsoon | 3 | 980 ± 182 | 137.0 | (682, 1278) |
| Aundh & Post-monsoon | 3 | 1720 ± 96 | 137.0 | (1422, 2018) |
| Bopodi & Pre-monsoon | 3 | 2030 ± 243 | 137.0 | (1732, 2328) |
| Bopodi & Post-monsoon | 3 | 1433 ± 68 | 137.0 | (1135, 1732) |
| Wakad & Pre-monsoon | 3 | 2413 ± 445 | 137.0 | (2115, 2712) |
| Wakad & Post-monsoon | 3 | 1530 ± 183 | 137.0 | (1232, 1828) |

[a] All significant at the $\alpha = 0.05$ level.

### 3.2. Physical characterization of microplastics

Microplastics were segregated under the optical microscope into different categories according to appearance in their shape, size and colour (Fig. 2).

Based on their shape, microplastics were classified as: fragment, film, foam, fibre and microbead, with microbeads being the least abundant. The abundance of microplastics of all the types of shapes was notably

**Table 3**
Pairwise comparisons between location, season, (season | location), and (location | season).

| Pre-condition | Factor level I - Factor level J | Mean Difference of MP (I-J) | SE | $p$ | 95 % CI of Difference |
|---|---|---|---|---|---|
| | Bopodi - Aundh | 382[a] | 137.0 | 0.049 | (1, 762) |
| | Wakad - Aundh | 622[a] | 137.0 | 0.002 | (241, 1002) |
| | Wakad - Bopodi | 240 | 137.0 | 0.316 | (-141, 621) |
| | Pre-monsoon - Post-monsoon | 247[a] | 111.8 | 0.048 | (3, 490) |
| Pre-monsoon | Bopodi - Aundh | 1050[a] | 193.7 | 0.001 | (512, 1588) |
| | Wakad - Aundh | 1433[a] | 193.7 | 0.001 | (895, 1972) |
| | Wakad - Bopodi | 383 | 193.7 | 0.214 | (-155, 922) |
| Post-monsoon | Aundh - Bopodi | 287 | 193.7 | 0.494 | (-252, 825) |
| | Aundh - Wakad | 190 | 193.7 | 1.000 | (-348, 728) |
| | Wakad - Bopodi | 97 | 193.7 | 1.000 | (-442, 635) |
| Aundh | Post-monsoon - Pre-monsoon | 740[a] | 193.7 | 0.002 | (318, 1162) |
| Bopodi | Pre-monsoon - Post-monsoon | 597[a] | 193.7 | 0.010 | (175, 1019) |
| Wakad | Pre-monsoon - Post-monsoon | 883[a] | 193.7 | 0.001 | (461, 1305) |

[a] The mean difference is significant at the 0.05 level.

**Table 4**
Seasonal variations of microplastic abundance in surface water of different rivers.

| Sr. No. | Sampling location (River) | Sample type | Study area (km) | Sampling sites | MP abundance (pre-monsoon) | MP abundance (post-monsoon) | Type of MPs | Reference |
|---|---|---|---|---|---|---|---|---|
| 1 | Orange -Vaal River system, South Africa | Water | 1458 km | 33 | 1.4 ± 2.6 microfibres/L | 2.3 ± 7.2 microfibres/L | – | Weideman et al. (2020) |
| 2 | River Ganga, India | Water | 2575 km | 10 | 0.051 ± 0.007 microplastic/L | 0.026 ± 0.004 microplastics/L | Rayon (54 %), acrylic (24 %), PET (8 %), PVC (6 %), PE (5 %) and nylon (3 %) | Napper et al. (2021) |
| 3 | Yellow River, China | Water and sediment | 214 km | 3 | 432.5 ± 240.54 n/L | 2510.83 ± 2971.27 n/L | Wet season water samples, PP (90.57 %). Dry season PBS (30.06 %), PET (23.38 %) PPC (18.43 %) | Qian et al. (2023) |
| 4 | XJ River | Water and sediment | – | 21 | 11.0 ± 3.08 items/L | 7.32 ± 2.36 items/L | Rayon (70.7 %), PE (13.0 %), acrylic (3.91 %), PVA (3.91 %), PP (2.17 %), PET (1.96 %), PA (1.52 %), PE 1.30 %, and PS (1.30 %) | Zhao et al. (2024) |
| 5 | Mula River, India | Water | 22.2 km | 3 | 1808 ± 697 particles/L | 1561 ± 167 particles/L | Pre-monsoon season: EVA (50 %), PP (15 %), PE (14 %), PS (7.14 %), PC (7 %) and PE + PET mix (7 %). Post-monsoon season: EVA (58 %), PE (17 %), PP (17 %) and nylon (8 %) | Current study |

Note: PE: Polyethylene; PP: Polypropylene; EVA: Ethylene vinyl acetate; PET: Polyethylene terephthalate; PS: Polystyrene; PVA: Polyvinyl alcohol; PBS: Polybutylene succinate.

high, with a minimum microplastic prevalence observed for microbeads among all other shapes. Microplastic prevalence varied specifically between fiber and film, fiber and microbead, film and foam, film and fragment, film and microbead, foam and microbead, and also between fragment and microbead. While film was the majority shape of microplastic at Wakad for both the seasons, pre monsoon (42 %) and post monsoon (29 %), microbead was the least abundant and significant shape. A similar trend was observed at Bopodi where film was the major shape for both the seasons. At Aundh (L2), foam (29 %) type of microplastics were most abundant pre-monsoon, whereas film (31 %) was the leading microplastic type post-monsoon (Fig. 3). Clothes, ropes and packaging material, such as sacks, could be probable source of fibers, while breakdown of plastic bags and packaging materials can contribute to film type of microplastics in river water. Presence of residential establishments close to the river and open garbage dumping could be responsible for the entry of these polymers in river water. Additionally, proximity to industrial establishments and absence of scientific waste disposal adds on to the entry of plastic waste in river water.

High microplastics were found at the three selected locations and for all shape types, with a minimum microplastic prevalence at Wakad and microbead combination. High number of microplastics were found during both seasons and for all types of shapes, with a minimum microplastic prevalence for pre-monsoon and microbead shape combinations. Fragmented microplastics could be a result of breakdown of large plastic debris being dumped in river water and can be categorized as secondary microplastics (Amrutha et al., 2023). Wakad and Bopodi locations, with heavily populated residential areas along the riverbanks, also harbour numerous small and medium-scale industries distributed along the river. The enormous amounts of waste and sewage being dumped straight into the river is in line with the high film and fragment types of microplastics observed at these locations (Ranjan).

Microplastics observed in samples were divided, according to their appearance, in red, blue, yellow, black, brown and white/transparent colours. Microplastic prevalence for all colours was high, with minimum prevalence observed for red colour. Black was the prominent colour of majority of the microplastics from all three locations, and red colour the least, during the pre-monsoon and post-monsoon period (Fig. 3).

High microplastics were recorded at the three locations and for all colours, except at Aundh where red colour MPs were the least abundant (Fig. 3). It was slightly high at Bopodi and for red combination. High microplastics were recorded during both seasons and for all colour combinations, with minimum microplastic for red colour post monsoon. Hence black was most abundant and red the least prevalent colour of MP recorded. During the summer season (pre-monsoon), 34 %, 34 % and 38 % was the distribution of black microplastics at Wakad, Aundh and Bopodi respectively. This abundance increased post-monsoon and the contribution of black microplastics to the total microplastic count increased to 59 %, 57 % and 49 % for Wakad, Aundh and Bopodi, respectively (Fig. 3). Packaging bags and bottles could be the probable sources for white/transparent microplastics, while black microplastics

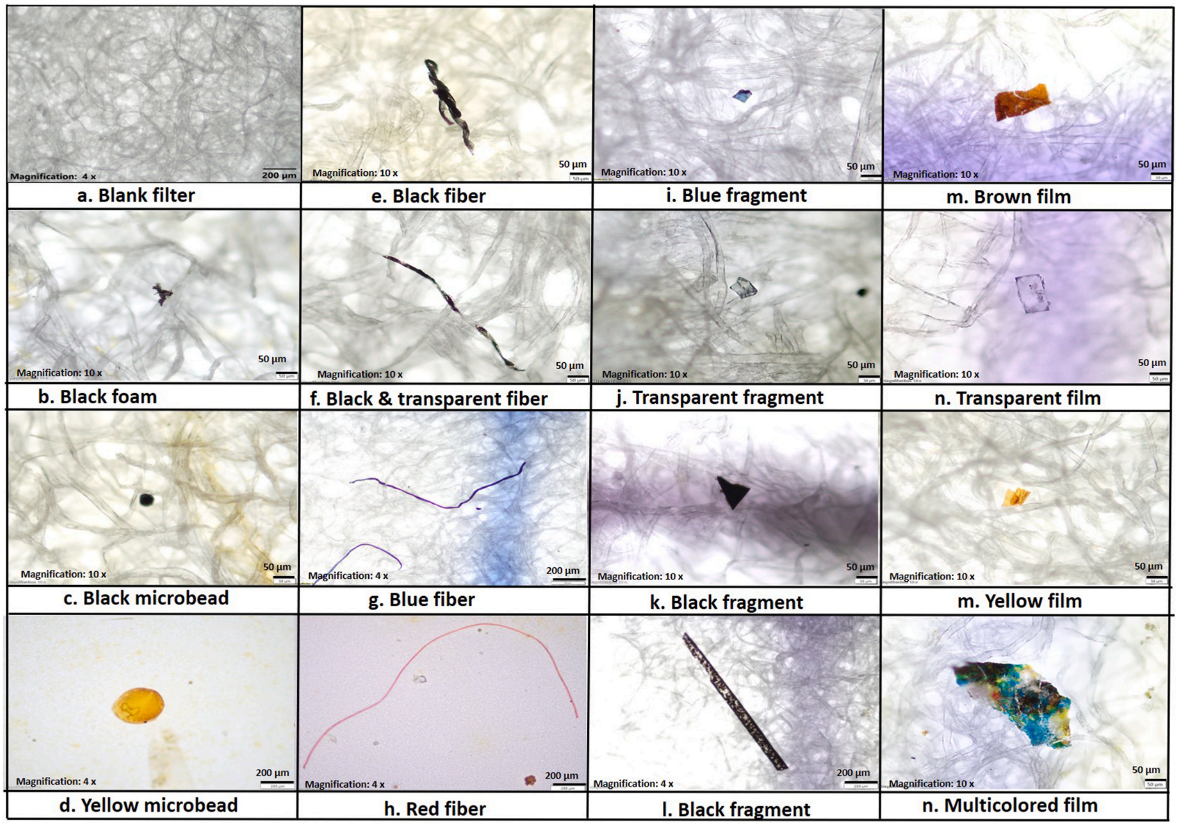


**Fig. 2.** Microscopic images of various types of microplastics obtained from all water samples (pre- and post-monsoon).

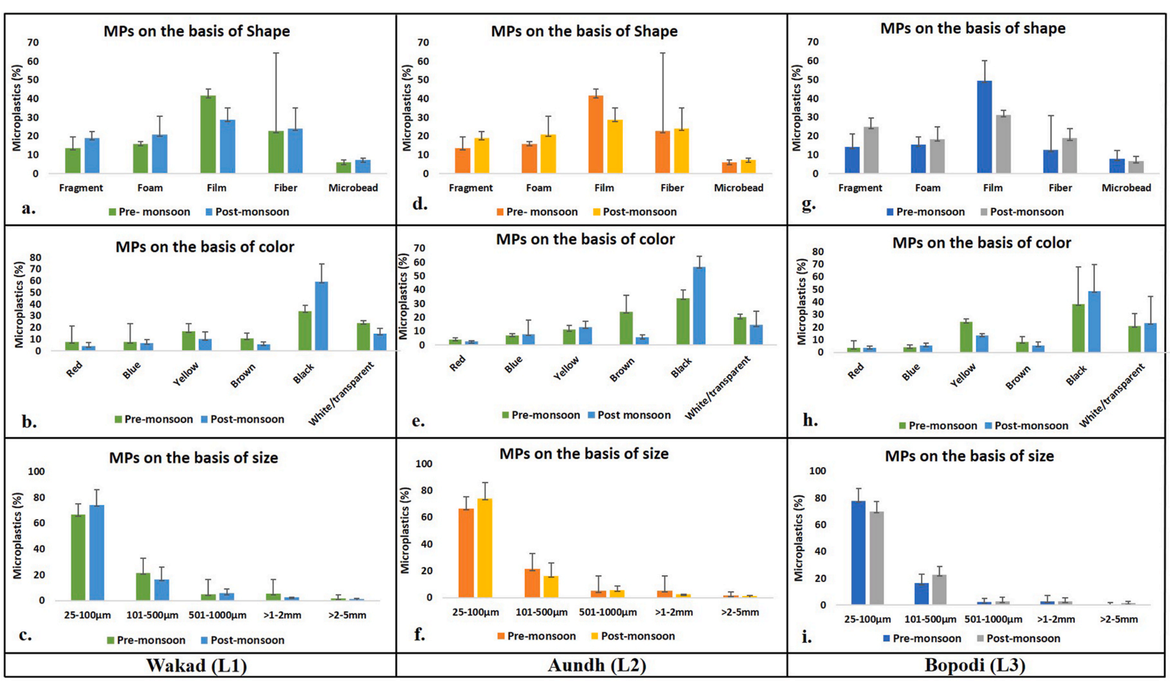


**Fig. 3.** Comparative chart of characteristics of microplastics in Mula River water (pre-monsoon and post-monsoon). MP: Microplastic.

can be suggested to primarily originate from vehicle tyres, plastic used for mulching in fields, single use plastics and other such domestic sources (Zhao et al., 2024). Pune is a developing city with extensive construction and urbanization. Dumping of construction materials along river beds leads to the leaching of plastic polymers from paint and other construction materials and could be another potential source for coloured microplastics in river waters.

Microplastics were divided into four categories according to particle size (25–100 μm, 101–500 μm, 501–1000 μm, 1000–2000 μm and 2000–5000 μm). The microplastic prevalence of all sizes was high with microplastic of size >2–5 mm showing minimum abundance for both seasons and at all three locations, followed by MPs of size >1–2 mm. The microplastic prevalence varied between 25 and 100 μm and the higher sizes, as well as between 101 and 500 μm and the higher sizes ($p < 0.001$). High microplastic prevalence was recorded at the three locations, with minimum microplastic prevalence at Aundh for 500–1000 μm sized microplastics. Lesser microplastics were recorded at Aundh for sizes greater than >1–2 mm, at Bopodi for sizes greater than >1–2 mm, and at Wakad for size >2–5 mm. Microplastics of size 25–100 μm were the most abundant at all the three locations, Wakad (69 %), Aundh (65 %) and Bopodi (78 %) in the pre-monsoon season. Similarly, microplastic abundance was 74 %, 80 % and 70 % for Wakad, Aundh, and Bopodi, respectively, in the post monsoon season.

It was clear from the study, that microplastics of size below 100 μm were dominating, indicating prominent entry of this size MPs in river, and increased fragmentation of plastic debris in river water. Similar results were reported from river Ganga (Ranjan) followed by other studies (Baldwin et al., 2016; Lahens et al., 2018; Zhao et al., 2024). The small size of microplastics makes it easier to be ingested by aquatic animals, and increases the risk associated with the presence of microplastics in food chain. It has been proven that 20 μm sized microplastics can enter organs, and microplastics of size 20–100 μm can easily cross cell membrane and placenta (Barcelo et al., 2023). Hence microplastic fractions of this size are crucial for risk assessment, as smaller particle sizes intensify toxicity and enhance the hazardous nature of these emerging pollutants.

### *3.3. Polymer characteristics*

The Mula River water samples were dominated by diverse plastic polymers, including Ethylene-vinyl acetate (EVA), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polycarbonate (PC) and nylon (Fig. 4).

All the FTIR spectra were confirmed as per the literature reported by Jung et al. (2018). FT-IR spectra of PE is characterized by absorption peaks at wave number 2913-2846 $cm^{-1}$ and smaller peak at 714 $cm^{-1}$ which correspond to -$CH_2$ stretching and rocking deformations respectively (Fig. 4b). Although FT-IR spectra of EVA and PE are very similar, the main difference between the two is the presence of less prominent peaks at 2921 $cm^{-1}$ and 2851 $cm^{-1}$ in EVA, which are sharp and prominent in the PE spectra. Additionally, prominent peaks at 1727 $cm^{-1}$ and 1010 $cm^{-1}$ in the FT-IR spectra of EVA, corresponding to C=O and C-O stretch, make it different from PE spectra (Fig. 4a). PP spectra is identified by characteristic peaks at 2952-2872 $cm^{-1}$ caused due to C-H asymmetric/symmetric stretch. Peaks at 1449 $cm^{-1}$ and 1372 $cm^{-1}$ are due to $CH_2$ and $CH_3$ bend (Fig. 4c). Peak at 3267 $cm^{-1}$ in Fig. 4d confirms the identity of nylon type of polymer formed by N-H stretch, while peak at 1542 $cm^{-1}$ is caused due to N-H bend/C-N stretch. PC is characterized by 1508 $cm^{-1}$ signifying aromatic ring stretch and 828 $cm^{-1}$ signifying aromatic C-H out of plane bend (Fig. 4e). The PS spectra represents characteristic peaks at 3024 $cm^{-1}$ (aromatic C-H stretch), 2847 $cm^{-1}$ (C-H stretch), 1457 $cm^{-1}$ ($CH_2$ bend) and 537 $cm^{-1}$ caused by aromatic ring out of plane bend (Fig. 4f). Another polymer identified was a blend of PE and PET, with characteristic peaks of both the polymer types present in the spectra (Fig. 4g).

Six types of polymers from pre monsoon season, and four types of polymer components from water collected during the post-monsoon season, were identified (Fig. 5).

The diversity in the type of microplastics was reduced in the post monsoon season, as is expected due to the flushing mechanism of river systems. Types of polymers in the pre-monsoon season included EVA (50 %), PP (15 %), PE (14 %), PS (7.14 %) and PC (7 %) and PE + PET mix (7 %). Water samples from the post-monsoon season showed presence of only four types of polymer components, EVA (58 %), PE (17 %), PP (17 %) and nylon (8 %) (Fig. 6) and Supplementary Table 2.

As evident from the polymer distribution (Fig. 6), EVA was the most prominent polymer type in river water at all locations and in both the seasons. Different studies have reported varied types of MPs in river water across different seasons (Table 3). This distribution is determined by the prominent sources of MPs entering the river water in the area of study. While rayon was the predominant type of MP reported in XJ River (Zhao et al., 2024) and in Ganga river water (Napper et al., 2021), EVA was the dominant MP in the current study. EVA is a co-polymer of ethylene and vinyl acetate and is a resilient plastic foam material generally utilized for sealing. EVA microplastics are commonly produced from the plastic wraps and hot melt adhesives (Liong et al., 2021). EVA foam is very similar in appearance to polyethylene foams, however, EVA foams have a far more rubbery and resilient feel. This improves the recovery of materials, making it suitable for use in physically demanding applications. Fibrous and fragmented microplastics composed of PE and PP have been the most common type of microplastics detected in studies on surface waters (Tsering et al., 2021; Singh et al., 2021). Prevalence of PE, as well as PE and PET blend polymers, indicates pollution from plastics used in packaging, packing and storing materials, as well as plastics used for making bunds across rivers. Such blended fibres are also being increasingly used in automobile industries due to their increased toughness and tensile strength, as compared to PE or PET (Delva et al., 2019). While PE and PP type of MPs with lower densities can travel far in water, microplastics like PVC and PET sink and become less common on the water surface due to their higher densities. This may explain the higher detection of EVA and PE type of MPs in river water in the current study, as well as in the previous study on Godavari river water (Sekar and Sundaram, 2023). The results obtained are also aligned with the higher abundance of microplastics, and increased prevalence of EVA and PE, in the water sample collected from river section passing through the industrial belt near Wakad area (L1), thereby indicating potential involvement of industrial sources to be the main reason for the increased occurrence of EVA microplastics in Mula river. This data can be used as a baseline for the future studies on monitoring the migration and transformation of EVA microplastics in the environment, and will aid in framing policies and interventions to mitigate plastic pollution in rivers from land-based sources.

## 4. Conclusion

Microplastic pollution in freshwater sources exacerbates the water resource crisis in cities and towns and leads to a wide range of potential impacts on human and animal life. Anthropogenic activities are the main reason for the increasing microplastic pollution, and hence study of the different ecosystems and identification of sources of plastics in river water assumes importance. This study revealed the prevalence and abundance of microplastics in the Mula River, Pune, India, at a depth of 0.5 m, before and after the monsoon season, in the stretch of 22.2 km within the Pune city limits. The average microplastics in Mula river water during pre-monsoon (1808 ± 697 particles/L) was higher than in the post-monsoon season (1561 ± 167 particles/L). This variation may be attributed to multiple factors, including regional rainfall, topography of the area and improper disposal of plastic waste. Season was found to play a significant role in microplastic abundance with notably high post monsoon prevalence. Film was the majority shape of MP at Wakad for pre-monsoon (42 %) and post-monsoon (29 %). A similar trend was observed at Bopodi, where MP abundance at pre-monsoon was 50 % and post-monsoon (31 %). Whereas in Aundh, foam (29 %) type of microplastics were most abundant in pre-monsoon and film (31 %) in post-monsoon. Black was the prominent colour of majority of the microplastics for all three locations during the pre-monsoon and post-monsoon period indicating wear and tear of tyres to be a prominent source of MPs in river water. For all the locations in all the seasons majority of MPs were in size range 25–100 μm, indicating wear and tear of larger plastic particles. EVA, a copolymer of PE and vinyl acetate, was clearly the most common polymer in the Mula river water. Higher abundance of microplastics in river stretch near industrial area, and

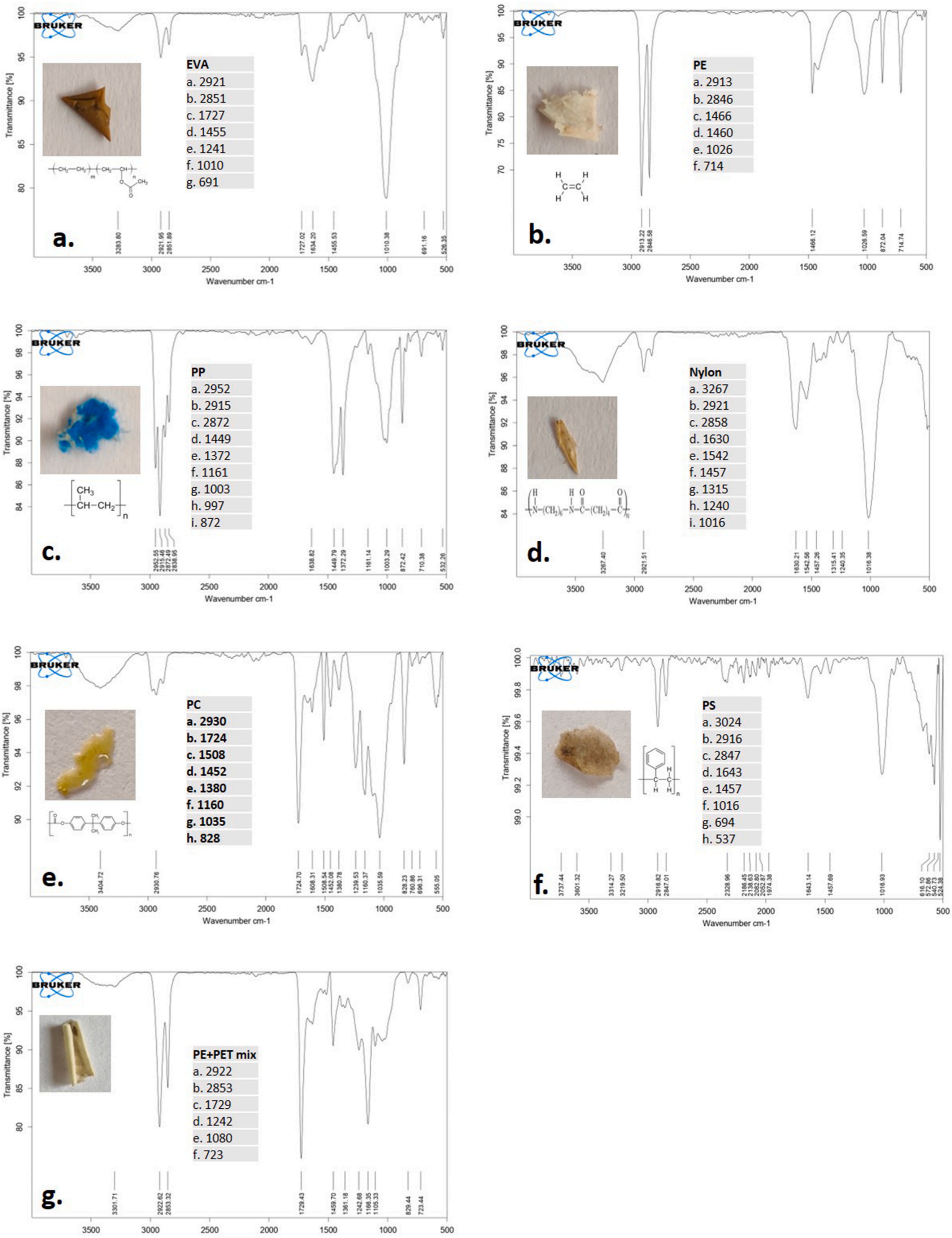


**Fig. 4.** FTIR spectra of representative microplastics present in Mula river water.

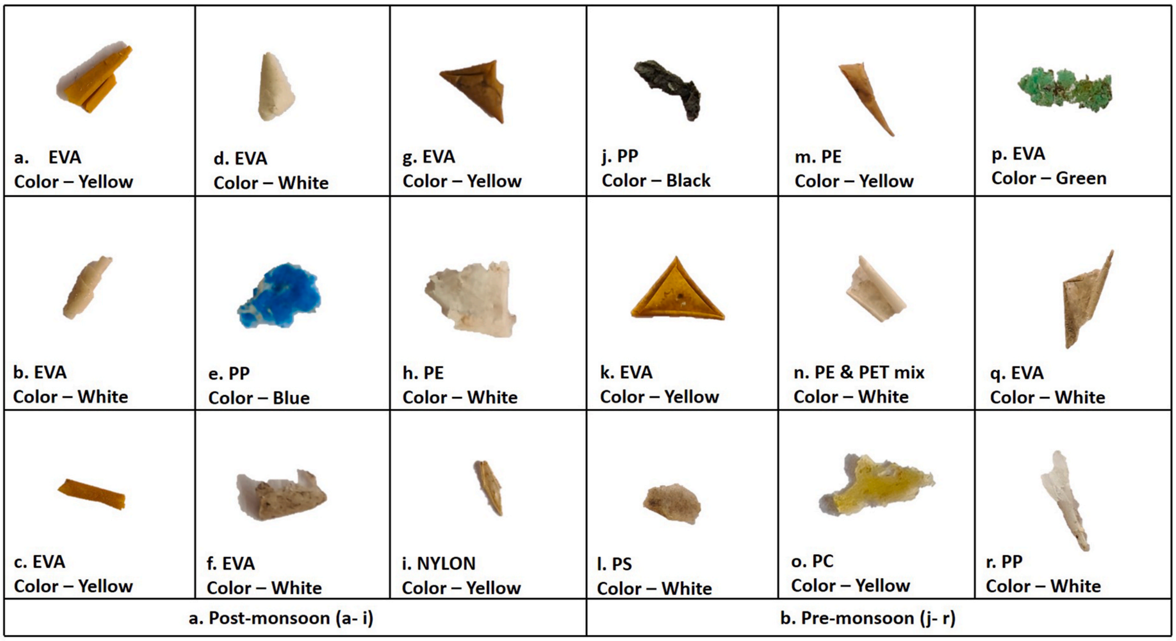


**Fig. 5.** Some of the representative particles selected for FTIR-ATR analysis and polymer composition identification. All the representative particles were in the range 2–5 mm.

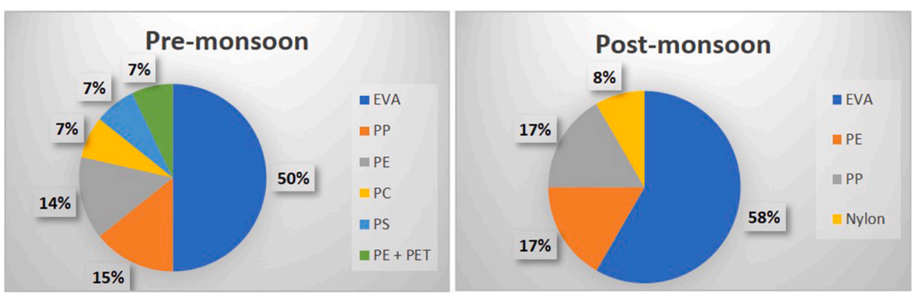


**Fig. 6.** Polymer distribution in pre-monsoon and post-monsoon season in Mula river.

prevalence of EVA and PET + PE blended plastic reiterates open waste disposal from industrial establishments points as a probable cause of pollution of freshwater systems, and calls for further investigations to validate the major sources of MP pollution, the migration route and transformation, and mitigation strategies of microplastics. Among the major factors responsible for the Mula river pollution, unplanned urban development along the river emerged a potentially prominent cause. Further detailed studies will aid in understanding and accurately identifying other point, and non-point sources of microplastic pollution in other parts of the Mula River and its associated waterbodies.

## CRediT authorship contribution statement

**Meenakshi Verma:** Writing – original draft, Methodology, Investigation, Data curation. **Pooja Singh:** Writing – review & editing, Validation, Resources, Project administration, Investigation. **Vishal Pradhan:** Writing – review & editing, Investigation, Formal analysis. **Manikprabhu Dhanorkar:** Writing – review & editing, Supervision, Conceptualization.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126091.

## Data availability

Data will be made available on request.

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