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Did the COVID-19 pandemic play a role in the spatial and temporal variations of microplastics? Evidence from a tropical river in southern India

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ABSTRACT

Personal protective equipment (PPE) use has increased because of COVID-19, producing more microplastics (MPs). The pandemic's impact on MP pollution in Indian rivers is little understood. In this study, the Netravathi River in Karnataka was investigated for the spatiotemporal distribution of MPs. The MPs abundance, size, and categories varied seasonally, with a higher concentration during the monsoon seasons. The reduction in rainfall during MON20 and the COVID-19 lockdown can be the reasons for the significant decrease in the MP concentration when compared to MON19. Polyethylene and polyethylene terephthalate were the most abundant polymers, with a shift from polyethylene to the latter (74 %) during post-monsoon season post-lockdown. The situation of MP pollution in Western Ghats can be mitigated with the aid of appropriate waste management of plastic trash and greater public awareness about the disposal of single-use plastics, which has risen significantly during the COVID-19 pandemic.

The ubiquitous nature of microplastics (MPs) and their negative impact on ecosystems make it crucial to take necessary measures. The smaller size of MPs makes them more harmful than more extensive plastic materials (Wright et al., 2013). The trophic transfer of MPs through the food chain and the ability of MPs to accumulate other environmental pollutants raise the level of concern (Yuan et al., 2022). The increasing concentration of MPs in the oceans demands investigation into their sources, of which rivers are the major route for MPs from the terrestrial environment to the marine ecosystem (Skalska et al., 2020). Different studies have accentuated the significance of rivers in the transport of MPs (Rodrigues et al., 2018a; van Wijnen et al., 2019; Eo et al., 2019). For example, Karthik et al. (2018) compared the distribution of MPs in relation to river transport, tourism, and fishing activities and found more MPs on beaches adjacent to river mouths. Also, the types of MPs obtained suggested a dominance of land-based sources.

The spatial distribution of MPs in beach systems is mainly affected by anthropogenic factors and the physical characteristics of associated basins (Talbot and Chang, 2022). Urbanization is the mainly responsible for the spatial variation of MPs concentration in the catchment (de Carvalho et al., 2021). This is because the MPs' magnitudes are influenced by factors such population density and the presence of industries, solid waste management units, and wastewater treatment plants (Sá et al., 2022). Furthermore, physical factors such as precipitation and the hydrodynamics of the catchment play a role in the temporal variation of MPs (Sá et al., 2022; Talbot and Chang, 2022). Some studies have shown higher MPs during the monsoon season (Gündoğdu et al., 2018; Alam et al., 2019). This is mainly due to the higher plastic load from land transported to the freshwater system through increased surface runoff associated with heavy rainfall (Amrutha and Warrier, 2020). Heavy precipitation and flooding events can significantly increase MP concentrations (Gündoğdu et al., 2018).

Microplastics degradation is a very slow process that can be caused by biotic and abiotic factors (Klein et al., 2018). The most prominent way of degrading most polymers is photooxidation (Hepsø, 2018). Fragmentation further reduces MPs size and increases their surface area, enhancing their ability to degrade into smaller particles (Hepsø, 2018). Greater exposure time indicates a higher degree of MPs weathering. This weathering leads to further fragmentation of MPs into even smaller particles, and the increased surface area can result in more degradation due to their higher reactivity (Klein et al., 2018). Such tiny particles

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produced by degradation will be more bioavailable to aquatic organisms.

The COVID-19 pandemic has had a significant impact on human behaviour, including changes in consumption patterns and waste management practices. The increase in single-use plastic usage and the use of personal protective equipment (PPE) during the pandemic has contributed to an increase in plastic waste, including MPs (Silva et al., 2021). The increase in plastic waste from COVID-19-related activities lead to an increase in microplastic distribution in basins and coastal areas (Devereux et al., 2023). Additionally, the pandemic has also affected waste management systems, with many facilities being closed or operating at reduced capacity due to safety concerns, leading to the improper disposal of plastic waste (Sharma et al., 2020). Furthermore, the pandemic has resulted in a decrease in tourism and shipping activities, which may have impacted the distribution of MPs in coastal areas (Nigam et al., 2022). While research on the relationship between COVID-19 and microplastic pollution is limited, it is important to consider the potential impact of the pandemic on plastic waste and its subsequent effects on the environment, including the distribution of MPs in basins and coastal areas.

There is scarce data on the impact of the COVID-19 pandemic on the increasing threat of MP pollution. Further, the role played by rivers also needs to be investigated in the transport of these MPs to the oceans. The Western Ghat region is ecologically sensitive and have rich biodiversity. As such, the rivers flowing through these regions should be inspected for MP contamination, especially considering potential changes in consumption patterns and waste management practices during the pandemic. In addition, only a few studies have discussed the relationship between MP distribution and different environmental factors that govern their fate in these rivers (Amrutha et al., 2023).

Currently, only one study has investigated the seasonal distribution of MPs in the riverine environments of Karnataka (Amrutha et al., 2023), and there is a lack of information on the input of MPs from these rivers into the Arabian Sea, including any potential effects from the pandemic. The aim of this baseline paper is to conduct, for the first time, a temporal investigation of MPs along the Netravathi River Basin, which flows through the Western Ghats, rural and urban Dakshina Kannada, Karnataka, before emptying into the Ullal coastal area of the Arabian Sea, and to determine if COVID-19 influenced the presence and distribution of MPs.

The Netravathi River (Fig. 1a and b), one of the largest rivers originating from the Western Ghats and flowing through southern Karnataka in southwest (SW) India, was selected for this baseline study. The entire catchment area of the Netravathi River (basin and coastal zone) was chosen as one of the hotspots under the world's biodiversity conservation projects (Molur et al., 2011). The river's headwaters are in the Bangrabalige valley and the Yelaneeru Ghat in Kudremukh, Chikkamagaluru District, Karnataka. The river flows 126 km and is an important water source for Mangalore and Bantwal (Gowda et al., 2015). During the monsoon season, the river overflows, which can harm the nearby areas (Karnataka State Pollution Control Board, 2019). The basin's upper reaches are mainly thick forests comprised of vegetation and forest plantations, while the lower reaches include highly populated urban areas (Fig. 1b).

According to the Karnataka Pollution Control Board (2019), the lower stretch of the river is polluted due to the lack of proper wastewater treatment facilities in adjacent towns and villages. There is a wastewater treatment plant (WWTP) with a capacity of 20 million liters a day (MLD) located in the downstream part of the river basin at Bajal. The Mangalore Special Economic Zone Limited reuses the treated water from this plant for industrial purposes (Matsunaga, 2018). The report also states that Mangalore is one of the industrial hubs of Karnataka and is located downstream of the river basin, with many industries functioning, such as Mangalore Power Company, Mangalore Refineries and Chemical Limited, Canara Spring Limited, Chemical Fertilizers, and others. Plastic pollution in adjacent areas of the Netravathi River has also been reported (Sulochanan et al., 2014).

During the monsoon season (July 2019 and July 2020; $n = 14$, hereafter referred as MON19 and MON20) and after (January 2020 and February 2021; $n = 16$, hereafter referred as POM19-20 and POM20-21), samples of surface water from different parts of the river Netravathi were collected. The study area receives rainfall during the southwest monsoon season between June and September. We collected the samples in July because, historically, July is the wettest month in the Mangalore region. A total of 60 samples were collected for all the seasons, and the details of the sampling locations are provided in Supplementary Table S1. Samples could not be taken from two sites (L1 and L2) during the MON20 due to COVID-related restrictions in the Ghat region. 10-l stainless steel bucket was used to collect 125 l of surface water from each sampling location, by vertically immersing the steel bucket into the river under the water surface to a depth of 50 cm (Lin et al., 2018; Yan et al., 2019). The water samples were immediately filtered through a stainless-steel sieve (Haver Standard) having a mesh size of 0.3 mm. The residue collected on the top of the 0.3-mm sieve was transferred into glass beakers, packed, and safely transported to the laboratory for further analysis.

For the isolation of MPs, modified NOAA laboratory methods were used to analyse MPs in water samples (Masura et al., 2015; Rodrigues et al., 2018a, 2018b). The residues present in the beakers were passed through a stack of two sieves with diameters of 5 mm and 0.3 mm at the

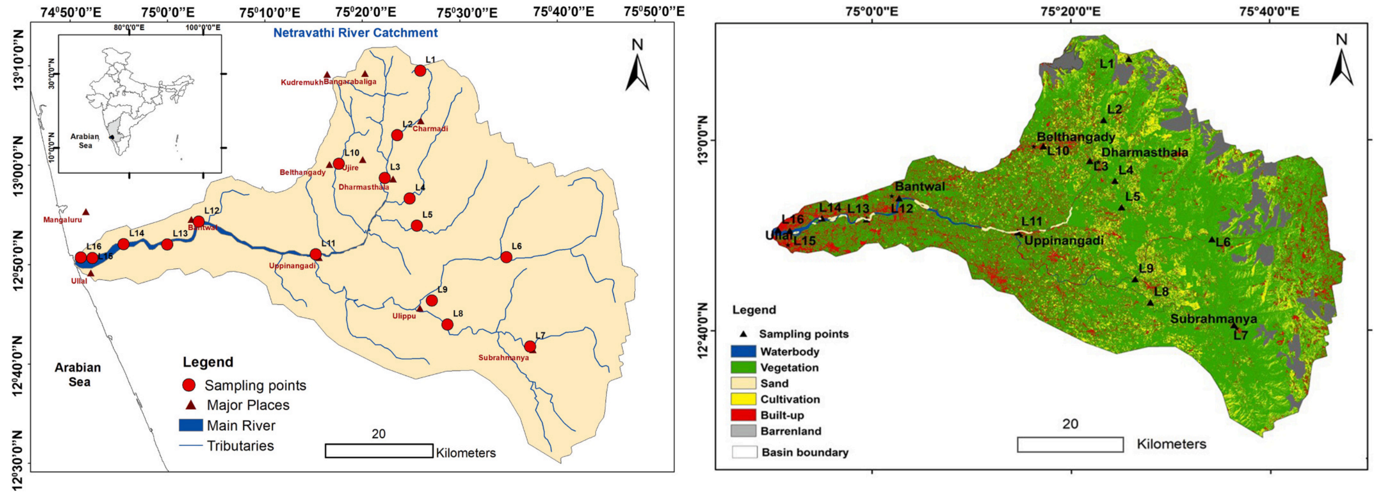

Fig. 1. Maps of the (a) Netravathi River basin in southwest India, and (b) a regional land use-land cover image (Sentinel-2 satellite data).

top and bottom, respectively. The residue from the latter sieve was dried in a glass beaker in a hot-air oven at 75 °C for 24 h (Masura et al., 2015; Rodrigues et al., 2018a, 2018b). To eliminate the organic matter, the wet peroxide oxidation (WPO) method was employed (Rodrigues et al., 2018b). The WPO method involved the following steps: A 0.05 M ferrous solution was prepared by adding 7.5 g of $FeSO_4.7H_2O$ to 500 ml of water and 3 ml of concentrated H_2SO_4. This was followed by adding 20 ml of the prepared ferrous solution to the glass beaker containing the residue solids and adding 20 ml of 30 % hydrogen peroxide. This solution was heated up to 75 °C (Masura et al., 2015; Rodrigues et al., 2018a, 2018b). The removal of organic matter was followed by the density separation method. For this method, we used $ZnCl_2$, as it is known to effectively separate higher-density polymers (Rodrigues et al., 2018b; Coppock et al., 2017). The solution was passed through a density separator, which helped separate the floating MPs from the denser inorganic material. The supernatant was carefully separated and passed through stacks of two sieves with diameters of 1 mm (top) and 0.3 mm (bottom) and then dried.

Using Nikon stereo zoom microscope with a 40× magnification, the particles that were moved to the watch glasses were studied for their abundance, shapes, and colour. During the visual identification, the criteria from Hidalgo-Ruz et al. (2012) were used to make sure that no non-plastic items were picked up. The isolated MPs were transferred into pre-weighed glass vials, which were weighed again. The MPs were classified based on morphological characteristics into foams, films, fibres, fragments, and pellets.

The polymer identification of MPs was performed using the Shimadzu IRSpirit FTIR with the QATR-S Single Reflection ATR Accessory. Percent transmission was recorded at a range of 3500–500 cm^{-1}, with a resolution of 4 cm^{-1}, and 25 scans were carried out per sample. A background scan was conducted before introducing each sample, and the ATR crystal was cleaned with chloroform before every sample. For ATR-FTIR identification, 24 (MON19), 13 (POM19-20), 15 (MON20), and 23 (POM20-21) MPs were chosen. The types of polymers were verified by checking the IR spectra obtained with the reference library available on OpenSpecy, an open-source software programme (Cowger et al., 2020).

The surface features of a total of 12 MPs representing all the seasons were examined using a scanning electron microscope (SEM)—an EVO MA18 instrument with Oxford EDS (X-act), operated at 5 kV. The MPs were fixed on stubs, sputter-coated with gold, and examined at different magnifications. Energy dispersive X-ray spectroscopy (EDS) was used to qualitatively examine the elemental composition of the samples.

The number of microplastics (MPs) that the Netravathi River carried was ascertained using the river's monthly discharge during July 2019 (monsoon) and the MP concentration for that month. Since there was no monthly discharge numbers for July 2020 (monsoon), the MP load was estimated for the monsoon season of 2019 only. Compared to the other three seasons, the study area received extremely high SW monsoon During July–August 2019 (India Water Resources Information System, Government of India, n.d.; Supplementary Fig. S1). The monthly average discharge of the River Netravathi during MON19 was measured at the Bantwal site, a part of the lower stretch of the river (data from the Central Water Commission). To calculate the MP load (surface), the monthly discharge was multiplied by the surface area and MP abundance (Eo et al., 2019). The river's surface discharge can be calculated by multiplying the discharge data with the depth proportion, which is ratio of the sampling depth (0.5 m) to the river's total depth (D in metres; Eo et al., 2019; Napper et al., 2021, Eq. (1)).

$$\text{Surface discharge} = \text{discharge} \times 0.5/D \tag{1}$$

Veerasingam et al. (2016b) and Rodrigues et al. (2018a) explain how ATR-FTIR spectra can be used to estimate the relative levels of surface oxidation of MPs. This is achieved by calculating the carbonyl index (CI) of specific polymers. The CI is a parameter used to measure the amount of light-induced photooxidation in the environment. This value increases with exposure time (Rodrigues et al., 2018a; Veerasingam et al., 2016a, 2016b). Here, the CI for polyethylene (PE) samples has been calculated using the following equation (Eq. (2), (Rodrigues et al., 2018a)):

$$\text{Carbonyl Index (CI)} = \text{A1}/\text{A2}. \tag{2}$$

where, A1 is the absorbance at the wavelength of the carbonyl group and A2 is the absorbance at the wavelengths of the reference peaks of polymers (Rodrigues et al., 2018a; Veerasingam et al., 2016a; Endo et al., 2005).

The degree of weathering was determined by calculating the CI absorption at 1715 cm^{-1}, a common indicator of PE degradation, with absorbance at 720 cm^{-1} used as a reference peak (Endo et al., 2005; Rodrigues et al., 2018b). The relative level of surface oxidation can be determined from the CI value, which is expressed as the ratio of low, medium, and high surface oxidation. A high surface oxidation value corresponds to MPs with a carbonyl index value >0.31, medium to MPs between 0.16 and 0.3, and low to MPs between 0 and 0.15 (Rodrigues et al., 2018a). An increase in surface oxidation indicates an increase in the degree of weathering of MPs (Endo et al., 2005).

The data was analysed using PAST 3 software (version 3.22; Hammer et al., 2001). As the samples did not pass the Shapiro-Wilks test for normality, non-parametric statistical analyses were conducted. The Kruskal-Wallis test was used to compare microplastic abundance seasonally, followed by Dunn's post-hoc test. Descriptive statistics such as mean, maximum, minimum, and standard deviation (SD) values were also obtained for MP abundance in the samples.

At every stage of the analysis, precautions were taken to prevent contamination. The only materials used were glass and steel. The analysis was done in a clean laboratory with little interference from the staff and under controlled ventilation. Before beginning experiments, the workbenches were regularly cleaned. Double-distilled water was used to clean the equipment, and Milli-Q was used to produce the solutions. To ensure there was no contamination, the prepared solutions, Milli-Q, and double-distilled water were filtered through a 0.3-mm stainless steel sieve. The laboratory equipment was thoroughly cleaned with pre-sieved double-distilled water and covered with aluminium foil. Throughout the analysis, cotton lab coats and nitrile gloves were worn.

The abundance, size, and categories of MPs obtained from the study varied seasonally (Supplementary Figs. S2 and S3). The mean (±SD) abundances of MPs in the water samples were 288 ± 591.23 (MON19), 15.06 ± 15.46 (POM19-20), 36.86 ± 23.12 (MON20), and 70.5 ± 61.22 MPs/m^3 (POM20-21) (Fig. 2; Supplementary Tables S2–S5). A higher proportion of larger (1–5 mm) size fractions were observed in the water samples during both monsoon seasons (Figs. 3 and 4a). The abundance of MPs was very high in MON19, compared to the other three seasons.

In comparison to MON19 (56 MPs/m^3), the sampling site L1 (source region) showed a lower abundance of MPs during POM19-20 (8 MPs/m^3). Similarly, L2 (Charmadi), one of the sites in the upstream region, showed a decrease in MP abundance following MON19 (MON19 = 64 MPs/m^3; POM19-20 = 8 MPs/m^3). Samples could not be taken from these sites during the next monsoon season (2020) due to COVID-related restrictions in the Ghat region. The post-monsoon season of 2021 (L1 = 16 MPs/m^3; L2 = 32 MPs/m^3) witnessed a comparatively higher number of MPs compared to that of 2020 (L1 = 8 MPs/m^3; L2 = 8 MPs/m^3). The comparatively lower distribution of MPs here could be due to lesser human intervention resulting from relatively lower population distribution (Population Census, 2011).

Dharmasthala (L3; 208 MPs/m^3) and Neriya Hole (L4; 96 MPs/m^3) had higher numbers of MPs during MON19. These sampling sites are located near famous pilgrim centres, and surface runoff is the main way in which pollutants, including MPs, reach rivers in these regions (Vanapalli et al., 2021). During POM 2019–20, no MPs were obtained from the water samples collected from these sites. The reduction in rainfall and surface runoff during the post-monsoon could be a reason

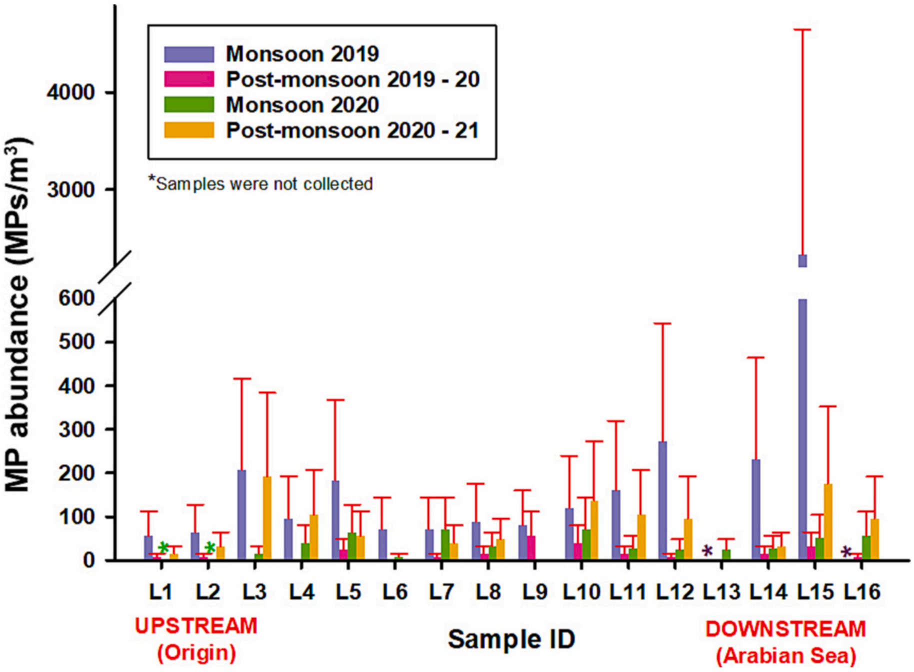

Fig. 2. Seasonal variation of MP abundance in the surface waters of the river Netravathi.

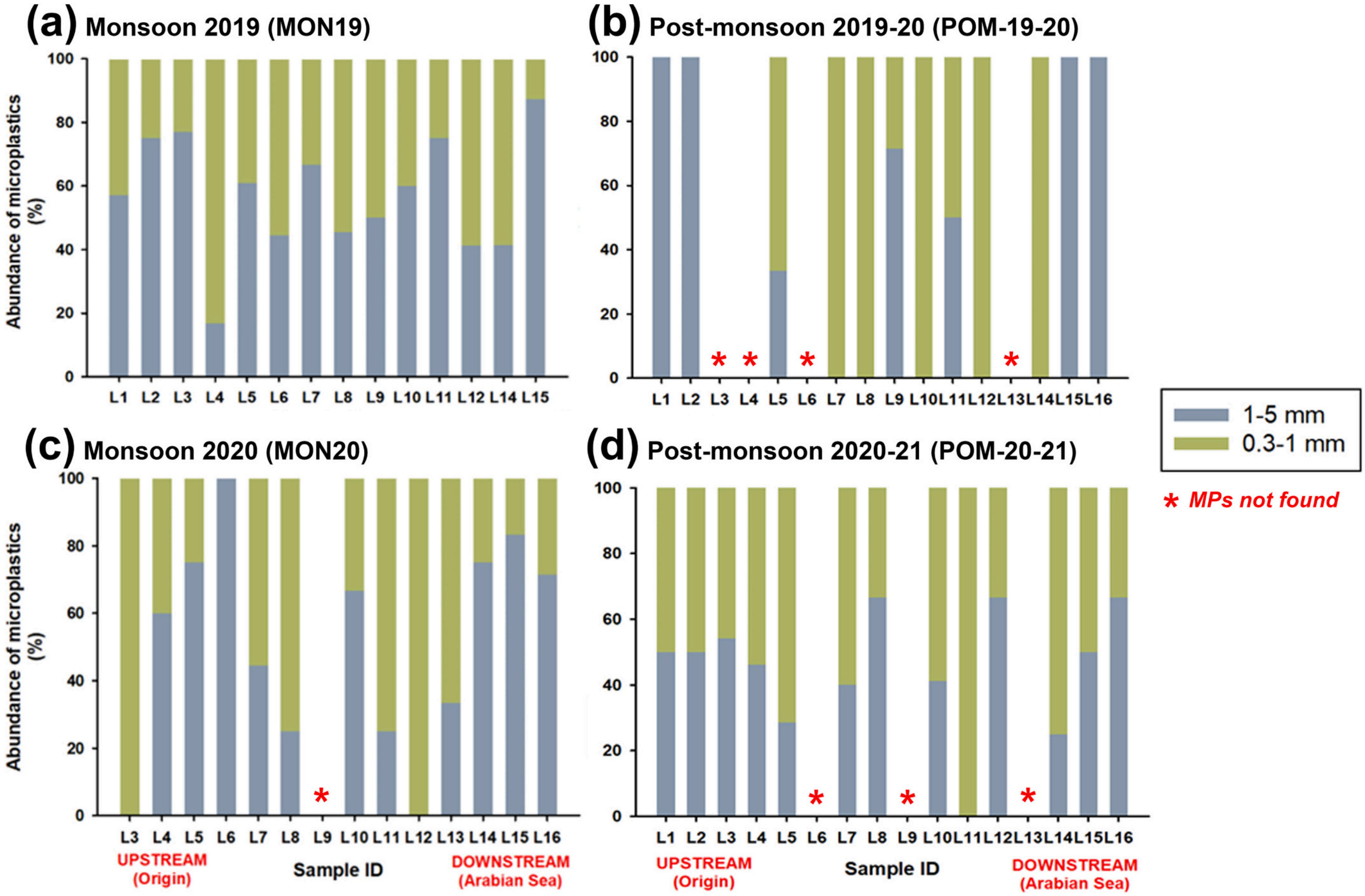

Fig. 3. Size distribution of microplastics obtained from the water samples of the river Netravathi during monsoon 2019, post-monsoon 2019–2020, monsoon 2020, and post-monsoon 2020–2021.

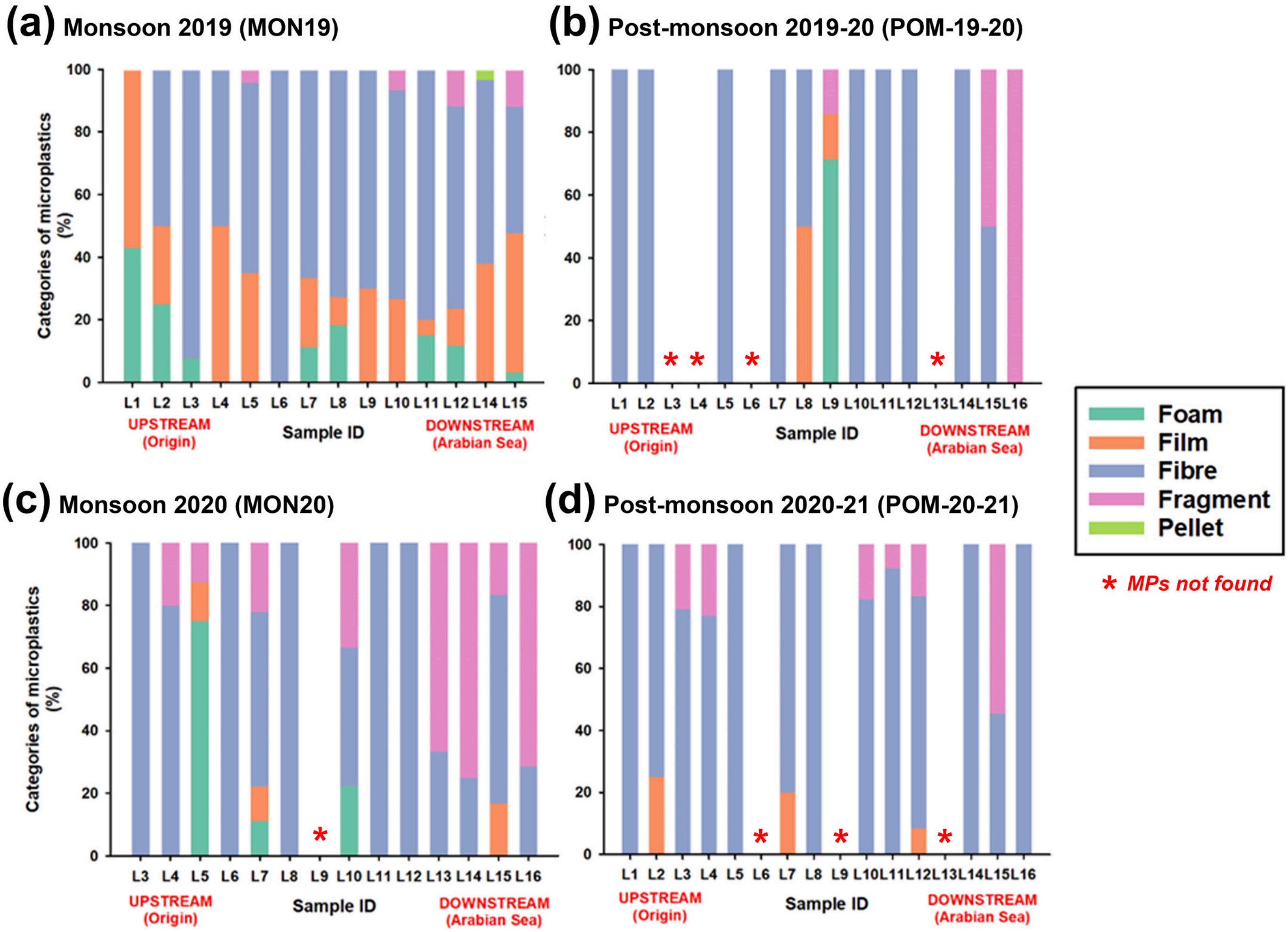

Fig. 4. Seasonal variations of the average values of the different (a) size range and (b) categories of microplastics obtained from the river Netravathi.

for the absence of MPs, and the lower velocity could also increase the likelihood of MP deposition in the sediments (He et al., 2020). However, in the case of these two sites, these regions are high-energy environments, and the increased turbulence in the water column would keep the MPs in suspension and likely to be carried downstream (Kumar et al., 2021).

These sites are near famous pilgrim centres that have high levels of activity and witnessed higher number of MPs during MON19. However, the MP concentration during the next monsoon season was decreased (Dharmasthala: 16 MPs/m^3; Neriya Hole: 40 MPs/m^3). One of the reasons for this decline can be the rapid decrease in the number of tourists and pilgrims during this period due to restrictions imposed on account of COVID-19 (Nigam et al., 2022). The decrease in the number of pilgrims and tourists can lead to the decline in the potential debris to be washed downstream during the monsoon. The significant increase in the number of MPs during the post-lockdown period (POM20-21) validates this reasoning (Dharmasthala: 192 MPs/m^3; Neriya Hole: 104 MPs/m^3). The number of MPs during MON19 is comparable to POM20-21. Fibres were the main category of MPs in these sites, and their concentration decreased during MON20.

Plastic littering and the presence of cloth waste discarded by tourists were observed along the shoreline of the sampling site, L5 (Kapila River). The monsoon-induced surface runoff can result in the flow of these plastic materials into the river. The abundance of MPs from this site decreased dramatically following the monsoon season of 2019–20. By the end of the monsoon, most of the MPs in the river might have flowed towards their downstream regions (Napper et al., 2021). The MPs showed an increase in their concentration during MON20 and a slight decrease during POM20–21.

In addition, a clean-up programme was conducted during May 2020 to clean the river Kapila by a group of 80 villagers from Shishila, and ended up removing all kinds of waste, including ten sacks of plastic waste (Deccan Herald, 2020). This action could have contributed to the reduction of MPs in the water samples. The concentration of MPs in this sampling site was lower compared to other sites, except during MON19, indicating that the river is relatively less polluted by MPs. This lower number could be attributed to the lower population density and the absence of major tourist centres in the upstream region of the river (Population Census, 2011).

No MPs were detected at site L6 (mid-stream of the Gundya River at Gundya National Highway) during the post-monsoon seasons of 2019–20 and 2020–21. The concentration of MPs during MON20 (8 MPs/m^3) was also very low compared to MON19 (72 MPs/m^3). The Gundya River basin is a tributary of Kumaradhara, which is a major tributary of the river Netravathi. Generally, the concentration of MPs at this site is comparatively low. The water samples collected from this site had only fibres present, which contaminated the location (Figs. 4b and 5). This result may be due to the effective domestic waste management system practiced in the area, which prevents the presence of films, foams, and fragments (Amrutha and Warrier, 2020).

The river Gundya at site Hosamatta (L9), located downstream of river Gundya, had a relatively higher number of MPs during MON19 (80 MPs/m^3), which decreased during POM19–20 (56 MPs/m^3). As previously mentioned, no MPs were detected from the upstream portion of

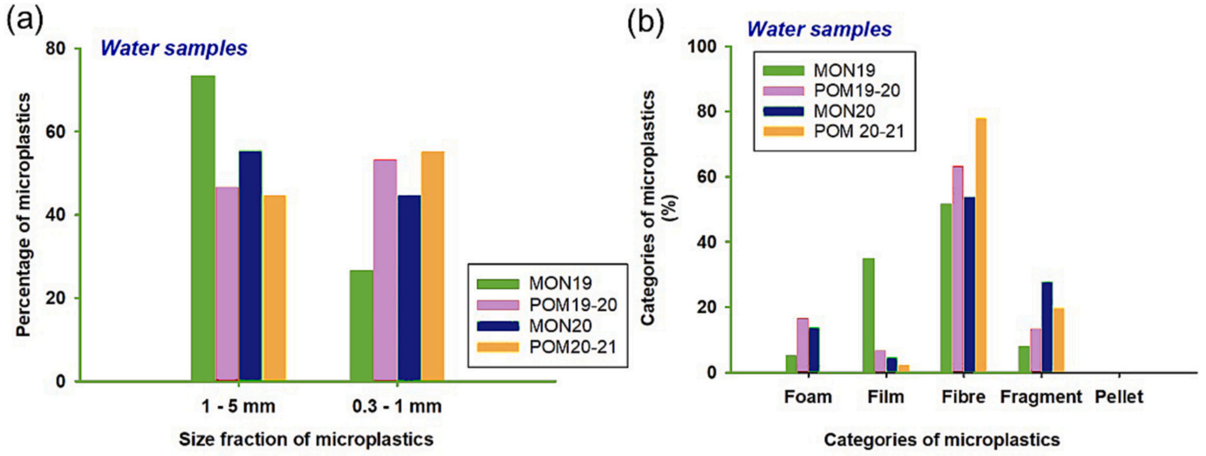

Fig. 5. Percentage of different categories of microplastics obtained from the river Netravathi during MON19, POM19–20, MON20, and POM20–21.

the site, suggesting that the primary source of pollution during POM was local. During the fieldwork, a significant amount of plastic litter was observed to have been washed away and accumulated in a low-energy environment (Supplementary Figs. S1c, d, e and S2a). The subsequent two seasons did not show any MPs in the water samples.

During both monsoon seasons, water samples collected from the river flowing near Subrahmanya (L7), an important pilgrim centre, had a comparatively higher MP concentration (72 MPs/m^3). There was also a decline during the post-monsoon season. The heavy rainfall during MON19 might have resulted in the resuspension of MPs that were already deposited in the sediments, causing the plastic materials to transfer to the water column (Gündoğdu et al., 2018). The water samples collected from the sampling site, L10, showed a higher concentration of MPs during MON19 (120 MPs/m^3). The site is located upstream of a dam, Laila Dam, across the river, in a small town called Belthangady. Microplastic abundance is generally higher in the upstream portion of a dam or reservoir than in the downstream part (Watkins et al., 2019). However, during POM19–20, the abundance decreased by three times (40 MPs/m^3).

Belathangadi, the region where L10 is located, experienced flooding during the monsoon of 2019. The flooding might have resulted in the removal of most MPs from the catchment, which could explain the lower concentration of MPs during POM 2019–20. The abundance of MPs increased during MON20 (72 MPs/m^3) but was lower than during POM19–20. However, the concentration increased significantly during POM20–21 (136 MPs/m^3). From the seasonal variation, it can be inferred that the main reason for the MP contamination at this site is anthropogenic inputs. No MPs were detected at Site L13 (Thumbe). Due to logistical constraints, samples could not be collected during MON19. Furthermore, no MPs were found in the water samples obtained during the two post-monsoon seasons. However, MPs were observed during MON20. The location of L13 is in an interior region, away from urban roads, indicating a low level of microplastic contamination.

The downstream of the river from Uppinangady is reported to be polluted by the Karnataka Pollution Control Board (2019). The distribution of MPs in water samples collected from the sampling sites located at the lower stretches (L11, L12, L14, L15, and L16) behaved similarly, with higher concentrations during MON19, followed by POM20–21, MON20, and POM19–20. Samples were not collected from L16 during MON19. The sampling site, L11 (Sangam), is where the tributary Kumaradhara meets the Netravathi River, and it is located close to a temple. Most MPs obtained from this site were fibres, mainly derived from cloth waste.

Microplastics were reported from two sampling sites closer to the Arabian Sea, L16 (Bolar) and L15 (near the Netravathi bridge). L15 had the highest number of MPs during MON19 (2328 MPs/m^3), and the next three seasons saw a drastic decrease in the number of MPs present. The river flows through a populated urban area of Mangalore City, and a higher number of MPs were reported from regions with high population density, high urban land cover, and proximity to WWTPs (Talbot and Chang, 2022). Anthropogenic interventions, heavy rainfall, and riverine discharge contribute to the abundance of MPs in this location.

Regarding Bolar, the abundance of MPs increased during the three seasons (POM19–20 = 8 MPs/m^3; MON20 = 56 MPs/m^3; POM20–21 = 96 MPs/m^3). The concentration of MPs was comparatively higher during POM20–21 than MON20 for both L15 and L16. During post-monsoon seasons, L16 showed a lower concentration of MPs when compared to L15 and a slightly higher concentration during MON20. This difference might be due to the influence of tides on the distribution of MPs near the river mouth. Riverine currents predominate over tidal currents during the SW monsoon due to higher river discharge (Bhat, 1995).

One serious issue at L15 is the practice of people throwing plastic waste into the river over the bridge. Recently, an awareness campaign was organized by the Mangaluru City Corporation in association with an NGO (APD Foundation - Hasiru Dala) and the Ullal City Municipal Council to inform people to refrain from dumping waste into the river Netravathi (Times of India, 2021). The obtained results indicate that a higher number of MPs were observed during the MON19 season, possibly due to the associated increase in the rate of surface runoff, which can carry plastic materials from adjacent areas to the river. The abundance of MPs in water samples during MON19 was significantly higher than in all other three seasons (Dunn's post-hoc test, $p < 0.01$). The Kruskal-Wallis tests also indicated a significant difference between sample medians for the different seasons (Supplementary Table S6). Rainfall is an efficient way to generate surface runoff (Xia et al., 2021). The rainfall can enhance surface runoff, which can transport terrestrial materials, including plastic debris, into the river system. The intensity of rainfall affects the strength of surface runoff required to transfer MPs from the river catchment areas to the river. During fieldwork, plastic littering in the catchment was observed (Supplementary Figs. S4 and S5). Moreover, the strengthening of hydrodynamics during rainfall can lead to the resuspension of MPs from sediments, increasing the abundance of MPs in the surface water (Ji et al., 2021).

After the end of the heavy rainfall event (MON19), most plastic materials may have been flushed to the sea, resulting in a reduction of MP concentration in the surface water (Napper et al., 2021). In addition, the concentration of MPs decreased during POM19–20 and increased during MON20, followed by an increase in concentration during POM20–21. However, the concentration of MPs during these seasons was still lower than during MON19. The results suggest that anthropogenic inputs are the primary source of MP contamination in the study area. The findings also highlight the importance of proper waste management practices, especially in areas with high population density and proximity to urban and industrial areas.

A significant decrease in the concentration of MPs in the water samples was observed during MON20 as compared to MON19. The variation in the amount of rainfall obtained during both years could be a reason for this difference. During MON19 (June–October 2019), the cumulative rainfall of the Dakshina Kannada district was 3765.75 mm, whereas during MON20, it was 3164.14 mm (India Water Resources Information System, Government of India, n.d.). Another possible factor could be the COVID-19 pandemic lockdown that was in place from March-end to June 2020. MP pollution drastically decreases when people have had a reduced ability to move around during lockdown periods, therefore, less plastic pollution is likely to wash into the rivers. The restrictions on tourism, pilgrimage, and other activities may have led to a reduction in the amount of plastic litter in the catchment area, which could have contributed to the decrease of MPs in the river Netravathi in the water samples.

The number of MPs obtained from water samples collected during the post-lockdown period (POM20–21, February 2021) increased compared to the previous season. The increase can be attributed to an upswing in tourism activities and the removal of restrictions on pilgrims. Fibres, primarily derived from cloth waste, were the major contributors of MPs during this period (Figs. 4b and 5; Supplementary Table S2). Nigam et al. (2022) found a significant decrease in litter during the lockdown period and an increase during the post-lockdown period. The abundance of MPs during POM20–21 is significantly higher than that during POM19–20 (Dunn's post-hoc test, $p = 0.003$).

The most abundant polymers identified in the water samples were polyethylene and polyethylene terephthalate (Fig. 6). During MON19, polyethylene was the dominant polymer, while both polymers were present in high concentrations during the succeeding season (Fig. 6). Interestingly, the post-lockdown period witnessed a lower concentration of polyethylene and a higher concentration of polyethylene terephthalate with respect to their preceding counter parts (Fig. 6). That is, the percentage of polyethylene decreased from 58 % (MON19) to 39 % (MON20) and 33 % (POM19–20) to 16 % (POM20–21). Similarly, the percentage of polyethylene terephthalate increased from 29 % (MON19) to 32 % (MON20) and 54 % (POM19–20) to 74 % (POM20–21). The decrease in littering during the lockdown imposed due to the COVID-19 pandemic from March 24, 2020, to June 2020 might have reduced the amount of terrestrial waste entering the water bodies. However, during the post-lockdown periods, with an increase in tourist activities and the number of pilgrims, the concentration of primary MPs, including microfibers, has increased, as indicated by the presence of polyethylene terephthalate in the water samples.

Photo-oxidation is the most efficient mechanism of degradation for most polymer types present in different environmental matrices (Hepsø, 2018). The degradation of microplastic materials continues until they become nanoplastics, which are more bioavailable (Rodrigues et al., 2018a). Exposure time plays an important role in the degradation of MPs (Chen et al., 2021). Additionally, the rate of degradation depends on environmental conditions, intrinsic and extrinsic properties of plastics, and/or the presence of additives in the polymers (Chamas et al., 2020).

In the case of water samples, the average CI values obtained are 0.41 (MON19), 0.20 (POM19–20), 0.37 (MON20), and 0.12 (POM20–21). Monsoon 2019 and monsoon 2020 exhibited comparatively higher CI values than the post-monsoon seasons. Several factors can influence the CI value of the polymer, including the prevalent weathering conditions during the sampling period (Prata et al., 2020). The high CI values of the samples indicate that these MPs were transported over long distances (Chen et al., 2021) and have undergone degradation over time. The higher rainfall that occurred during MON19 may have transferred most of the terrestrially aged MPs to the river. The intensity of plastic degradation is higher on land than in the oceans, where exposure to UV

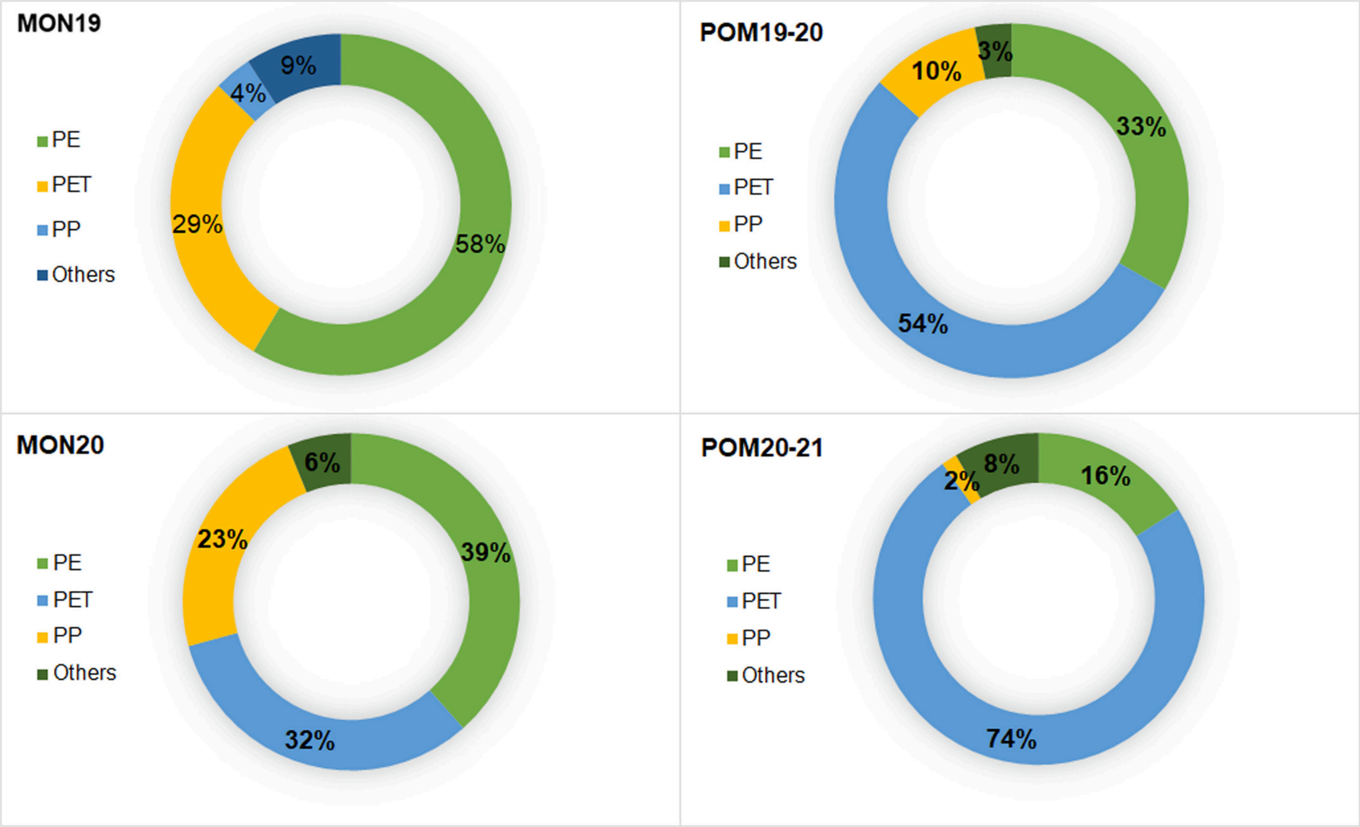

Fig. 6. Doughnut plots showing the abundance of the major polymers found in water samples collected from the river Netravathi during MON19, POM19–20, MON20, and POM20–21.

radiation and mechanical erosion is minimal (Veerasingam et al., 2016b). The present study observed a higher concentration of MPs in the water samples during MON19 when compared to all other three seasons. One of the main factors that determines the fate of MPs in a riverine system is precipitation. The concentration of MPs in the river system increases as the intensity of rainfall increases (Faure et al., 2015).

The dynamic nature of MPs concentration in the riverine environment is due to the influence of the surface runoff associated with the rainfall (Roebroek et al., 2021). The rainfall can result in the flushing of MPs that were present in the riverine catchment into the river (Talbot and Chang, 2022). Because of the higher intensity monsoonal rainfall received in the study area, the erosive effect of surface runoff may have increased. This would have resulted in the transfer of a large quantity of terrestrial sediments to the river, thereby carrying more MPs along with them. Microplastics deposited in the sediments of the river might have been resuspended in the water column (due to the heavy rainfall and strong hydrodynamic conditions), leading to increased MP fluxes into the Arabian Sea (Xia et al., 2021).

Due to the heavy rainfall that occurred during the 2019 season, the river Netravathi might have transferred a significant number of MPs to the estuary and to the Arabian Sea. The monthly surface load of plastic carried by the river can be calculated by multiplying the monthly discharge of the river with the abundance of MPs downstream (Eq. (1)). As the average monthly discharge of the river Netravathi during MON19 measured at the Bantwal site was available (data from the Central Water Commission, Government of India), an estimated amount of 1.12×10^9 MP pieces per day would have been released from the river Netravathi into the Arabian Sea.

Comparing this estimate with those from other studies shows that the release of MPs from the river Netravathi into the Arabian Sea is significant. Napper et al. (2021) estimated that about 1–3 billion (10^9) MPs are released from the Ganges into the Bay of Bengal every day, while another study conducted by Miller et al. (2017) calculated the amount of microfibres released from the Hudson River into the Atlantic Ocean and found it to be about 300 million microfibres per day. Note that these estimates were made based on the surface samples and did not consider the vertical distribution of MPs in the water column.

The morphological features of MPs were studied using SEM analysis of the MP particles (Unnikrishnan et al., 2023). The physicochemical properties of the polymer affect the degree of degradation and, in turn, influence the morphological characteristics of MPs (Zhou et al., 2018; Khaleel et al., 2022). The surface features of MPs, including cracks, scratches, and protrusions, reflect the intensity of degradation (Supplementary Figs. S6–S11). The wear and tear observed on some MPs may lead to the formation of smaller plastic materials. The reduction in the size of MPs increases their surface area, which can increase the risk of environmental pollutants accumulating on their surface (Tsering et al., 2021). The presence of multiple cracks, pits, and grooves indicates mechanical and oxidative weathering, which is a sign of polymer ageing (Zbyszewski et al., 2014; Warrier et al., 2022). EDS data revealed the presence of heavy metals such as iron, manganese, copper, cobalt, zinc, arsenic, cadmium, selenium, and lead. The ability of MPs to adsorb and absorb heavy metals can lead to their bioaccumulation in different trophic levels of the food chain (Crawford and Quinn, 2016).

The morphological features and chemical composition of MPs play an important role in their potential impact on the environment and human health. The degradation of MPs and the subsequent release of micro- and nanoplastics can enhance their bioavailability and bioaccumulation in the ecosystem (Rodrigues et al., 2018a). The presence of heavy metals on the surface of MPs can also pose a risk to the environment and human health. The accumulation of heavy metals in the food chain can have harmful effects, including damage to organs and tissues, hormonal imbalances, and the weakening of the immune system (Varó et al., 2019). The potential impacts of MPs on human health are still not fully understood and require further research. However, the presence of MPs in our environment and food chain highlights the need for effective waste management strategies and the development of sustainable alternatives to plastic materials.

This study reveals that microplastic pollution in the Netravathi River system is a seasonal phenomenon and can be attributed to human activities in the catchment areas. The highest concentration of MPs was observed during the MON19 season, which coincides with heavy rainfall and high surface runoff. This implies that the quantity of plastic debris carried by the river is dependent on the amount and intensity of rainfall received in the catchment areas. The reduction in the concentration of MPs during POM19–20 could be attributed to the effective clean-up programme conducted in the region, and the reduction in human activities due to COVID-19 restrictions. However, the post-lockdown period (POM20–21) saw a significant increase in the concentration of MPs, indicating that human activities, especially tourism and pilgrimage, contribute significantly to plastic pollution in the region.

Additionally, findings suggest that topography, hydrodynamics, and human activities all have an impact on the concentration and distribution of MPs in the Netravathi River system. The upstream regions of the river, which are less populated, showed lower concentrations of MPs compared to downstream regions. The study also found that the concentration of MPs varied in different size fractions, with larger fractions (1–5 mm) being more abundant during monsoon seasons. Furthermore, the concentration of MPs was higher at sites located near urban areas, pilgrimage centres, and tourist spots. This implies that microplastic pollution in the Netravathi River system is primarily caused by human activities, such as littering, poor waste management practices, and surface runoff from urban areas. The morphological features of MPs also revealed the degree of degradation and the presence of heavy metals, which can have harmful effects on the environment and human health. The presence of heavy metals on the surface of MPs highlights the need for stricter regulations on the use and disposal of plastic materials and the development of safer and more sustainable alternatives.

Another important aspect of the study is the influence of exposure time and environmental conditions on the degradation of MPs. The results suggest that exposure time and weathering conditions play a critical role in the degradation of MPs and the formation of smaller plastic particles, which can increase the risk of environmental pollutants accumulating on their surface. The bioavailability and bioaccumulation of MPs in the ecosystem can have far-reaching consequences, including damage to the environment and human health.

The water bodies of India witnessed lower pollution levels due to the lockdown restrictions on account of the COVID-19 pandemic (Yunus et al., 2020; Chakraborty et al., 2021). This is mainly because of the reduction in the discharge of domestic and industrial wastewater to the waterbodies and the decline in tourism and agricultural activities (Manoiu et al., 2022). However, the pandemic has tremendously increased the usage of single-use plastics due to medical and personal protection reasons, and their improper disposal has caused serious damage to the ecosystem (Reethu et al., 2023). These discarded plastic materials can be ingested by the organisms, or the organisms may get entrapped or entangled by them. In addition, the degradation of these plastic wastes into MPs can pose more harm to all organisms, including humans (Yang et al., 2022). Different studies have been done to investigate the impact of surgical masks on the environment, and the number of MPs released from the surgical masks varies among studies (Devereux et al., 2023). The large amount of microfibres releasing from a single mask is a matter of concern (Saliu et al., 2021). This study has microplastic data during the pre-lockdown period and the post-lockdown period. Even though the data shows the impact of the lockdown on the abundance of MPs, the MP load might be attributed to other factors, including the change in the intensity of rainfall during the period.

The proper management of plastic waste is the main solution to the crisis of microplastic pollution. Increasing public awareness about the importance of proper waste disposal will be the first step in curbing plastic littering and associated problems. (Yang et al., 2022; Saliu et al., 2021). Surface runoff is the main culprit in making the plastic reach the waterbodies. Therefore, the plastic littering should be reduced so that there will be a minimal plastic load entering the waterbodies. Furthermore, screens should be kept at the downstream portion of each streamlet, thereby decreasing the flow of MPs to the oceans. Clean-up programmes and employing new techniques such as the use of trash booms to collect floating plastic debris in rivers before it reaches the oceans can be done (Plastic Fischer, 2022).

CRediT authorship contribution statement

Amrutha, K. Conceptualization; Formal analysis; Investigation; Software; Visualization; Roles/Writing - original draft.

Anish Kumar Warrier Conceptualization; Funding acquisition; Investigation; Project administration; Resources; Software; Supervision; Visualization; Writing - review & editing.

Nelson Rangel-Buitrago Software; Statistical Analysis; Writing - review & editing

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.

Data availability

The data is provided in the supplementary file.

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Appendix A. Supplementary data

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