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## Pathway-specific microplastic dynamics in a Himalayan urban lake, India: insights on how continuous rainfall transforms microplastic characteristics and risk

Mozim Shafi,<sup>a</sup> Ayan Lodh,<sup>b</sup> Reyaz Hussain Akhooon,<sup>c</sup> Khalid Muzamil Gani<sup>c,d</sup> and Sudha Goel  <sup>\*ab</sup>

Microplastic (MP) pollution in freshwater systems has emerged as a pressing environmental concern, yet our efforts on prioritizing key pathways remain obscure. One of the promising approaches to reduce MP emissions is identifying key pathways to reduce their emissions at the source. To this end, we investigated how major MP pathways like stormwater runoff, wastewater treatment plants (WWTPs), littering zones, and laundry facilities show distinct MP characteristics in response to continuous rainfall in a highly urbanized lake. Our findings spotlighted WWTPs as persistent MP hotspots, with continuous rainfall substantially increasing MP abundance near stormwater outfalls. Fibers were dominant near WWTP and laundry sites, while stormwater and littering sites were dominated by fragments, signifying pathway-specific characteristics. Black particles were observed only near stormwater outlets and confirmed as rubber derived from tire and road wear abrasion. Continuous rainfall also affected the chemical profiles, particularly near stormwater outlets, resulting in the appearance of new polymers like polyurethane (PU), acrylonitrile butadiene styrene (ABS), and polyvinyl chloride (PVC). Furthermore, diversity indices also proved the transformative nature of continuous rainfall in reshaping MP community composition, highlighting the complexity of MP pollution dynamics. The risk assessment identified stormwater and WWTP pathways as significant contributors to MP-related toxicity. Overall, the findings showed how extreme weather events like continuous rainfall play a critical role in changing MP dynamics in freshwater systems and spotlighted key pathways and the need for targeted interventions, especially improving stormwater management and wastewater treatment to mitigate MP pollution.

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### Environmental significance

Microplastic (MP) pollution has emerged as a pressing environmental challenge with far-reaching implications for ecosystem health and, potentially, humans as well. While past research has largely focused on MP presence across various environments, limited studies have systematically compared distinct pathways and their pollutant signatures under continuous rainfall conditions. By identifying pathway-specific MP signatures, this study highlights that wastewater treatment plants and stormwater runoff serve as primary contributors of MPs, with distinctive polymer compositions and toxicity profiles. Continuous rainfall significantly alters MP abundance and community structure. Through comprehensive analysis, this study advocates for climate-resilient stormwater management and WWTP upgrades, offering a blueprint to mitigate pollution in rapidly urbanizing, climate-vulnerable regions.

## 1 Introduction

Plastic pollution, especially microplastics (MPs), has matured as an important scientific issue of global relevance. Defined as polymers of size <5 mm, MPs originate from the disintegration of plastic debris due to relentless environmental stresses like photodegradation, mechanical abrasion, and biological weathering.<sup>1</sup> MPs have been reported in all environmental compartments, with aquatic environments regarded as the ultimate receptors and sinks.<sup>2</sup> Plastic emissions into the environment are projected to persist, even under the global mitigation efforts for plastic waste reduction.<sup>3</sup> The annual plastic influx entering

<sup>a</sup>*Environmental Engineering and Management, Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal 721302, India.*  
E-mail: [sudhagel@civil.iitkgp.ac.in](mailto:sudhagel@civil.iitkgp.ac.in)

<sup>b</sup>*School of Environmental Science and Engineering, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal 721302, India*

<sup>c</sup>*Department of Civil Engineering, National Institute of Technology, Srinagar, Jammu and Kashmir 190006, India*

<sup>d</sup>*Institute for Water and Wastewater Treatment, Durban University of Technology, P. O. Box 1334, Durban 4000, South Africa*

freshwater systems is forecasted to increase from an estimated range of 9–14 million metric tonnes in 2016 to approximately 23–37 million metric tonnes by 2040.<sup>4</sup> This projected growth factor of approximately 2.5 will eventually increase the MP abundance in global water bodies over the next two decades.

The trajectory of MP research has evolved significantly over the past decade. Initially, researchers predominantly explored marine ecosystems, with surface waters identified as primary conduits for MP transport to oceanic environments.<sup>5,6</sup> This paradigm catalyzed a substantial proliferation of studies focused on freshwater MP dynamics.<sup>7</sup> The shift revealed that the prevalence of MPs in freshwater is related to or exceeds that reported in marine environments.<sup>8</sup> While studies have experienced significant growth in riverine systems, a notable knowledge gap persists regarding MP dynamics in lacustrine ecosystems.<sup>9</sup> However, the spatial distribution and characteristics of lakes within fluvial networks present a unique set of conditions that potentially amplify their exposure to MP pollution.<sup>10</sup> Unlike rivers, which are characterized by dynamic flow conditions, lakes act as natural sinks driven by complex internal processes. Their limited dilution capacity, extended residence time, high catchment-to-basin ratio, close anthropogenic proximity, and restricted outflow exacerbate MP accumulation, making local inputs far more evident than in riverine systems, where continuous flow tends to mask them.<sup>10</sup> Furthermore, lakes can serve as unique microcosms within freshwater networks, thereby serving as important indicators of local MP pollution sources, and could be a critical focal point for understanding the complex patterns of MP accumulation within freshwater systems.

The influx of MPs into surface waters occurs through a complex network of pathways, each contributing to the overall contamination burden. While effluents from wastewater treatment plants (WWTPs) have been a focus of many studies due to their consistent and measurable nature,<sup>11,12</sup> recent research has highlighted the significant contribution of other pathways, particularly stormwater runoff,<sup>13</sup> atmospheric deposition,<sup>14</sup> agricultural inputs,<sup>15</sup> littering,<sup>16</sup> and laundry activities.<sup>17</sup> Despite recent efforts to study MPs in aquatic environments worldwide, identifying and prioritizing key pathways through which MPs are released into these systems is difficult.<sup>18</sup> The dominance of specific pathways may be ecosystem-specific, influenced by factors such as local geography,<sup>19</sup> climate,<sup>20</sup> and human activities,<sup>21</sup> which complicates the development of standardized protocols for measuring MPs across different pathways, making cross-study comparisons difficult. While several studies have explored individual pathways of MP pollution,<sup>19,22</sup> there is limited research in understanding the relative contributions of multiple urban pathways within a single ecosystem simultaneously under different weather conditions, particularly in high-altitude urban Himalayan lakes. This study aims to address this gap by investigating the pathway-specific dynamics of MP inputs in Dal Lake, India.

In addition to these spatial factors, the distribution of MPs is also influenced by temporal features, particularly weather patterns. While studies have explained the variation in characteristics of MPs during discrete dry and wet spells,<sup>23</sup> there

remains a significant knowledge gap regarding the impacts of extreme weather events like continuous rainfall on MP abundance and characteristics. Unlike discrete storm events, continuous rainfall can lead to sustained high water levels, combined sewer overflows, and extended periods of runoff from urban landscapes. These conditions may result in complex MP transport and deposition patterns that differ significantly from those observed during intermittent wet and dry periods. Furthermore, the distribution of MPs, categorized by size, shape, and color, mirrors patterns commonly observed in biological communities.<sup>24,25</sup> However, the concept of MP communities remains underexplored, with only a few studies utilizing this approach to investigate differences and similarities in MP distributions across environmental settings.<sup>26</sup> These studies reported that MP communities show significant variability depending on environmental conditions, likely driven by spatiotemporal changes in MP sources. Therefore, this study leverages the concept of “MP communities” to further evaluate the impact of continuous rainfall on the structural characteristics of MPs to understand variabilities and connections across different pathways.

Therefore, addressing the MP challenge necessitates collecting reliable, localized data to inform solutions and establish meaningful compliance targets.<sup>27</sup> By simultaneously quantifying and characterizing MPs from multiple pathways, including WWTPs, stormwater runoff, littering sites, and laundry activities, this study hypothesized that with a change in weather conditions, MP characteristics would show pathway-dependent signatures, reflecting distinct source-transport mechanisms operating at the catchment scale. Understanding this is vital for prioritizing intervention strategies that first address the most significant pollution pathways. By bridging the gap between local-scale MP dynamics and global pollution trends, this study contributes to the broader scientific discourse on MP pollution and supports the development of scalable solutions for this pervasive environmental issue.

## 2 Material methods

### 2.1 Study area and motivation

Dal Lake, situated in Srinagar at coordinates 34°6'N latitude and 74°45'E longitude, at an altitude of 1583 meters, is the most famous tourist attraction in India. The city has a humid subtropical climate with an average annual rainfall of 720 mm and an average annual temperature of 24.1 °C.<sup>28</sup> The shoreline stretch of the lake is approximately 15.5 kilometers.<sup>29</sup> The study area was selected as most of the urban and recreational facilities are located in close proximity to the lake shoreline. As a result, multiple small WWTPs that treat wastewater from these facilities are discharged into the lake. In addition, at some places near the lake banks, there are laundering platforms where local washermen wash clothes manually, resulting in a direct discharge of washing effluent into the lake. Also, the main road runs along the periphery of the Lake and has a very high vehicular movement throughout the year. Due to poor drainage facilities in the area, many open stormwater culverts discharge untreated stormwater directly into the Lake. Therefore, by



leveraging the unique characteristics of intermittent distribution of MP pathways, this research strives to provide information on the priority pathways that drive MP contamination within the catchment and facilitate the development of evidence-based policies aimed at mitigating the pervasive threat posed by MPs.

## 2.2 Sampling strategy and collection

The sampling strategy was designed to assess MP pollution from the identified pathways and compare their contributions across different weather conditions Fig. 1. Sampling was conducted in two phases: first, before July 15, 2023 (dry spell), and second, after August 1, 2023 (post-continuous rainfall). The detailed sampling timeline is presented in Table S1. Sites include 3 at the outfall of stormwater culverts, 3 near WWTP outlets, 3 near littering zones, and 3 near laundering activities Table S2. Furthermore, to provide contrast and establish baseline conditions, 3 reference sites were selected along the banks of the nearby Nigeen Lake Fig. 1. While Nigeen Lake does receive limited wastewater inputs, it was selected because it experiences lower anthropogenic stress compared to Dal Lake. More specifically, it has a significantly lower population density, no major roads along its periphery, reduced stormwater discharge, and less commercial activity. These features collectively decrease the possibility of diverse and high-volume MP inputs, therefore making it a more representative low-impact system within the same geographic and climatic setting. This offers us an opportunity to evaluate background levels of MPs in

a relatively natural setting, thus helping in identifying priority hotspots of MP contamination.

Samples were collected at each site twice, capturing both the dry period and continuous rainfall periods. Here, a continuous rainfall period is when precipitation occurs continuously over an extended period, often lasting for several hours, days, or even weeks without significant dry spells in between. The sampling procedure was modified from previous studies.<sup>30,31</sup> Briefly, at each site, two replicate samples were collected from depths of 0 to 20 cm and sieved using a 1 L glass beaker. While the temporal resolution is limited to two events, we improved representativeness by collecting composite grab samples at each site, as supported by previous studies.<sup>12,31</sup> This approach was designed to balance logistical feasibility with a goal to achieve replication at the pathway level, which fits well with the primary goal of this study. The sieving process utilized 4.75 mm and 45 µm stainless steel sieves. Each sieving interval lasted 3 to 5 minutes to capture a representative water sample at each site. Residues remaining on the 45 µm sieve were carefully rinsed into a 500 mL glass bottle using distilled water.

## 2.3 Sample processing

Each sample was subjected to sequential sieving in the laboratory with varying mesh sizes (4.75 mm, 2 mm, 1 mm, 0.5 mm, and 0.045 mm) to categorize MPs into four size fractions (0.045–0.5, 0.5–1, 1–2, and 2–4.75 mm respectively) Fig. S1. Visible large plastics were carefully handpicked with tweezers and kept in Petri dishes with proper labeling for further analysis.

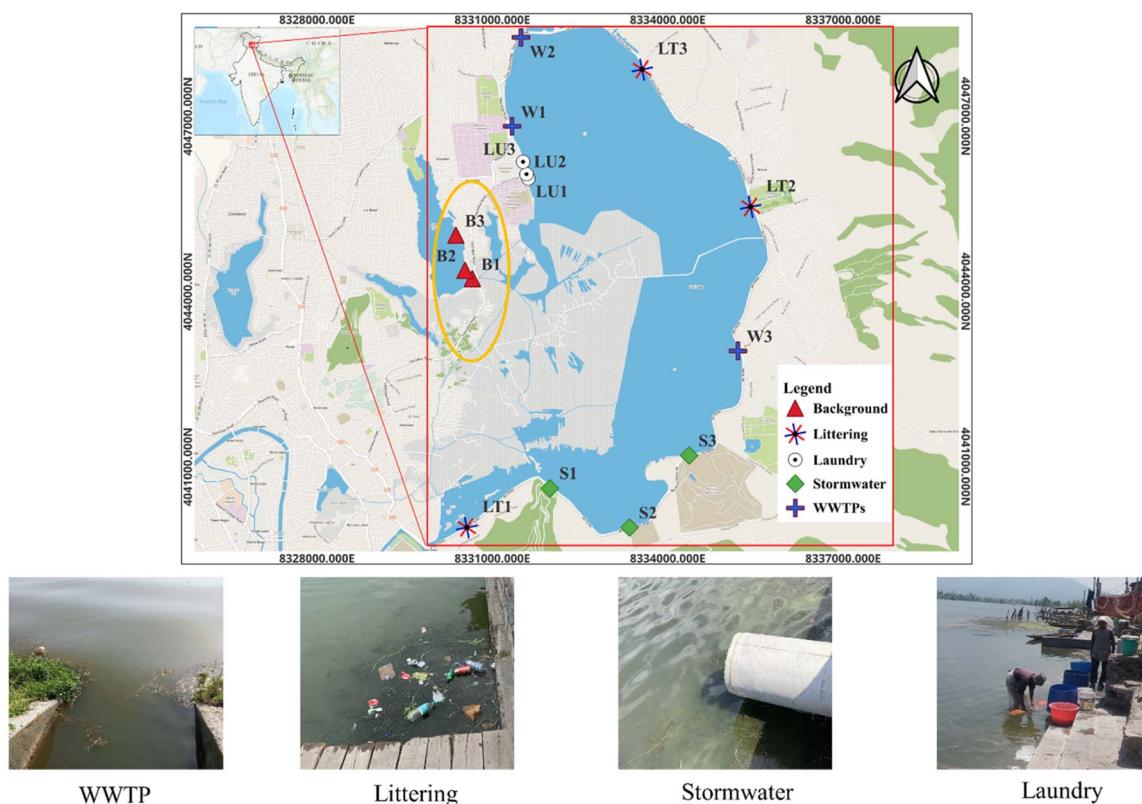


Fig. 1 Sampling locations representing distinct pathways.



Subsequently, the remaining sieved material was thoroughly rinsed with deionized water (Thermo Fisher Scientific; Barnstead Smart2Pure Model: 50 129 890) and transferred to separate glass beakers. After the initial sieving process, the samples were allowed to dry in an oven set at 60 °C until entirely moisture-free. Once dried, the samples underwent a three-step process (wet peroxide treatment, density separation, and vacuum filtration). The method followed for this study has been widely accepted and used in various studies.<sup>32,33</sup> Detailed processing in Text S1.

#### 2.4 Quantification and identification

Microplastics on air-dried filters were counted and photographed by systematically traversing the filters under a microscope (Motic BA400, Hong Kong, China) at  $\times 4$ – $\times 40$  magnification fitted with a 5-megapixel digital camera. The MPs were then categorized by color (red, blue, black, transparent, white, yellow, and green) and shape (fragment, fiber, film, pellet, and foam).<sup>34</sup> MPs large enough to be handled with metal forceps ( $>500 \mu\text{m}$ ) were carefully placed on microscopic cover glass slips and then sandwiched between two glass slides for polymer characterization.<sup>35</sup>

The polymer characterization was confirmed using an FTIR with an attenuated total reflectance (ATR) module (Alpha II compact FTIR, Bruker, Massachusetts, USA). Absorbance was measured in the 4000–500  $\text{cm}^{-1}$  spectral range at 4  $\text{cm}^{-1}$  resolutions. The resulting spectrum was then matched with reference spectra from Primpke *et al.*<sup>36</sup> and from the Bruker built-in library. Due to the complexity involved in MP characterization, we chose a subset of suspected MPs from each sample for polymer characterization. This subset accounted for more than 20% of the total particles observed in each sample during the visual analysis, aligning with the method used by previous studies.<sup>37–39</sup>

#### 2.5 Diversity index of MPs

The complicity of MP properties at different pathways was assessed using the MP diversity integrated index (MPDII). To calculate the MPDII, Simpson diversity indices (SDI) were first determined based on MPs characteristics (polymer, shape, size, and color) using eqn (1). (Li *et al.*, 2021; Wei *et al.*, 2022).<sup>24,40</sup>

$$\text{SDI} = 1 - \sum_{i=1}^S P_i^2 \quad (1)$$

where:  $P_i$  = proportion of category  $i$  (calculated as  $P_i = \frac{S_i}{S_{\text{Total}}}$ ).

$S_i$  = number of MPs in category  $i$ .  $S$  = number of categories.

SDI measures diversity by considering two key aspects: richness ( $S$ ) (number of different categories, *i.e.*, polymer, shape, color, and size) and evenness ( $P$ ) (how evenly individuals are distributed among the categories). Furthermore, based on the observed Simpson diversities, the MPDII was calculated using eqn (2) to reflect on MP community composition to understand the complexity of various pollution sources.

$$\text{MPDII} = (\text{SDI}_{\text{POLYMER}} \times \text{SDI}_{\text{SHAPE}} \times \text{SDI}_{\text{SIZE}} \times \text{SDI}_{\text{COLOR}})^{1/3} \quad (2)$$

If the value of SDI and MPDII is close to 1, it indicates greater diversity of MPs (Luo *et al.*, 2022).<sup>41</sup>

#### 2.6 Pathway-specific risk assessment

Currently, no widely accepted approaches exist to comprehensively understand the risk resulting from MP pollution. However, in this study, pathway-specific risk assessment of MPs was reported for both weather conditions by calculating the pollution load index (PLI) resulting from the concentration of MPs observed at each site. In addition, as different polymer types of MPs were observed, with each having a different toxicity level in the water, we further calculated the hazard index (HI) and pollution risk index (PRI) as additional measures to improve the risk assessment of MPs. This approach is currently highly reliable and well-accepted among researchers and has been used in many previous studies.<sup>42–44</sup>

The calculation formulas for the indices are as follows:

$$\text{PLI}_i = C_i/C_o$$

$$\text{PLI}_{\text{Pathway}} = \sqrt[n]{\text{PLI}_{\text{site-1}} \times \text{PLI}_{\text{site-2}} \times \text{PLI}_{\text{site-3}} \dots \text{PLI}_{\text{site-}n}}$$

Here,  $i$  represents a sampling site,  $C_i$  is the concentration of MPs at that site, and  $C_o$  denotes the baseline MP concentration. Here, the baseline concentration is defined as the minimum MP concentration observed at the background sites.  $C_o$  value was 0.42 particles per L in a dry spell and 1.4 particles per L after continuous rainfall.  $\text{PLI}_{\text{pathway}}$  represents the overall MPs pollution load index at each pathway.

$$H_{\text{site-}i} = \sum_{j=1}^m P_{ij} \times S_j$$

$$H_{\text{pathway}} = \sqrt[n]{H_{\text{site-1}} \times H_{\text{site-2}} \times H_{\text{site-3}} \dots \times H_{\text{site-}n}}$$

$P_{ij}$  represents the number of polymers obtained at the  $i$ th sampling site,  $j$  is the type of polymer,  $m$  refers to the number of observed polymer types, and  $n$  is the total number of sampling sites.  $S_j$  is the hazard score of polymers. The observed polymers and their respective  $S_j$  values were PP (1), PE (11), PET (4), nylon (50), PS (30), PU (556), PVC (5001), and ABS (6552).<sup>45</sup>

$$\text{PRI}_{\text{site-}i} = H_{\text{site-}i} \times \text{PLI}_{\text{site-}i}$$

$$\text{PRI}_{\text{pathway}} = \sqrt[n]{\text{PRI}_{\text{site-1}} \times \text{PRI}_{\text{site-2}} \times \text{PRI}_{\text{site-3}} \dots \text{PRI}_{\text{site-}n}}$$

where  $\text{PRI}_{\text{site-}i}$  represents the pollution risk index of MPs at site  $i$ , and  $\text{PRI}_{\text{pathway}}$  shows the overall pollution risk index of MPs at each pathway. The risk classification ranking is provided in the Table. S3

#### 2.7 QC/QA

Strict precursory measures regarding external contamination of MPs were taken through appropriate quality control and



assurance (QC/QA) procedures throughout the sampling campaigns and laboratory analysis. Several steps were included to reduce potential contamination of the samples. Plastic materials throughout field sampling and analysis were minimized, and standard laboratory decontaminations were employed to minimize the impact of potential contamination on sample processing. A total of 30 field blanks, 15 each in dry spell and after continuous rainfall, were prepared. Briefly, 1 L of filtered distilled water was prepared in a glass bottle in the laboratory and taken to the sampling site. The cap was kept open during sampling and then sealed after sampling. The field blank was transported to the laboratory and was analysed after similar treatment as environmental samples. Before experiments, all the reagents used were filtered through a Whatman glass microfiber filter (0.45  $\mu\text{m}$ ). All containers were rinsed with Milli-Q water, and aluminium foil covers were used throughout sample processing and extraction stages at every apparatus, reagent, and sample. All laboratory procedures were done inside a laminar fume hood to minimise airborne contamination. Also, procedural blanks were performed during each round of MPs analysis to identify any sources of contamination during analysis. Procedural blanks were evaluated using 1 L of distilled water and subsequently analyzed with the same procedure used for the real water samples. We did not observe any MPs in the field and procedural control samples except for a few PET fibers observed in dry spell in field blanks, which might have resulted from airborne contamination,<sup>46</sup> indicating negligible pollution during the analysis process. Therefore, the results were not adjusted for the field and procedural blanks. Furthermore, during sample analysis, some MPs may be lost as the density separation process is not 100% accurate. A recovery test was performed by introducing a known quantity of readily identifiable MPs into distilled water, which was then followed by the aforementioned sample preparation procedure more details in Text S2. The average recovery rates observed in this study were between 84% and 93% Fig. S2.

## 2.8 Data analysis

Data analysis and processing were carried out using R (Version 4.4.0) and Microsoft Excel 2021 software. Before data analysis, we used Shapiro-Wilk and Levene's tests to check the normality and equal variances, respectively. Shapiro-Wilk ( $W = 0.89\text{--}0.92$ ,  $p\text{-value} < 0.05$  for all groups) showed that the data followed a non-normal distribution and therefore non-parametric tests (Kruskal-Wallis for multiple groups comparison and Mann-Whitney  $U$  for pairwise comparisons) were used for subsequent analyses. Kruskal-Wallis test was followed by a Dunn post hoc test that allows for multiple pairwise comparisons of MP characteristics from different pathways. Further, Cramer's test was used to assess the strength of association between the shape and color of MPs.  $P$  values less than 0.05 were considered statistically significant for all the statistical tests. All the graphs and study area maps were plotted using Origin Pro software (version 9.8.0, 2021) and ArcMap software, respectively.

## 3 Results and discussion

### 3.1 MPs occurrence: spatiotemporal variations and impact of continuous rainfall

Fig. 2a displays the average MPs abundance observed in Dal Lake's surface water samples collected from different sites in both dry spell and after continuous rainfall. MPs were pervasive in all the samples collected. The average abundance from all sampling sites during a dry weather spell was  $5.9 \pm 3.55 \text{ p L}^{-1}$ , with a range of  $(1.1\text{--}12.3 \text{ p L}^{-1})$ . After continuous rainfall, the abundance increased to  $10 \pm 4.4 \text{ p L}^{-1}$ , with a range of  $(3.9\text{--}19.6 \text{ p L}^{-1})$ . Results from the Mann-Whitney  $U$  test showed a significant difference between the two weather conditions ( $U = 255$ ,  $p = 0.004$ ), with a higher abundance occurring after continuous rainfall. The increased abundance of MPs following continuous rainfall suggests a substantial influence of rainfall-derived mobilization of MPs in surface waters. Previous studies have also reported an increase in the abundance of MPs in surface waters after rainfall events. For example, in Donghu Lake, Wuhan, the MP abundance under equilibrium conditions was  $5.84 \pm 2.96$  particles per L, which significantly increased to  $8.27 \pm 5.65$  particles per L after rainfall.<sup>47</sup> This increase can be due to a combination of factors. Stormwater runoff can transport MPs from urban and informal settlements into the lake.<sup>48</sup> Atmospheric deposition contributes airborne MPs directly to surface waters.<sup>14</sup> Additionally, rainfall-induced changes in lake hydrodynamics can lead to sediment resuspension, releasing previously deposited MPs back into the water column.<sup>47</sup> Together, these processes contribute to the observed rise in MP abundance following continuous rainfall. In Dry spell, the highest average abundance was observed at W2 ( $12.3 \text{ p L}^{-1}$ ) and the lowest was observed at S2 ( $1.1 \text{ p L}^{-1}$ ). Similarly, after continuous rainfall, the highest concentration was observed at W2 ( $19.6 \text{ p L}^{-1}$ ) and the lowest at LT2 ( $3.9 \text{ p L}^{-1}$ ). The persistent high abundance of MPs at W2 is because this site is located very close to a drainage canal, where the catchment is mainly a residential area upstream. The low flow velocity in this canal, with the direct discharge of untreated wastewater from the surroundings, facilitates MP accumulation. These accumulated MPs are transported downstream during continuous rainfall, resulting in increased MP abundance at W2. A similar trend was observed at LT3, which is close to a similar drainage canal, resulting in a higher abundance of MPs after continuous rainfall. This aligns with the finding reported by Zhang *et al.*,<sup>49</sup> where a higher abundance of MPs ( $20.5 \pm 7.4 \text{ p L}^{-1}$ ) was observed in one of the stormwater drains resulting from the low flow velocity during rainfall from the nearby canal. In contrast, when comparing the observed results with background sites, a significantly lower average abundance of MPs ( $0.76 \pm 0.35 \text{ p L}^{-1}$ ) was observed ( $U = 141$ ,  $p < 0.001$ ) Fig. 2b. This difference confirms the localized impact across different sites due to site-specific differences in population density, local anthropogenic activities, and urban infrastructure. Comparative assessments of MP abundance across lacustrine ecosystems globally present methodological challenges arising from differences in research design and objectives. Nevertheless, we compared studies with similar



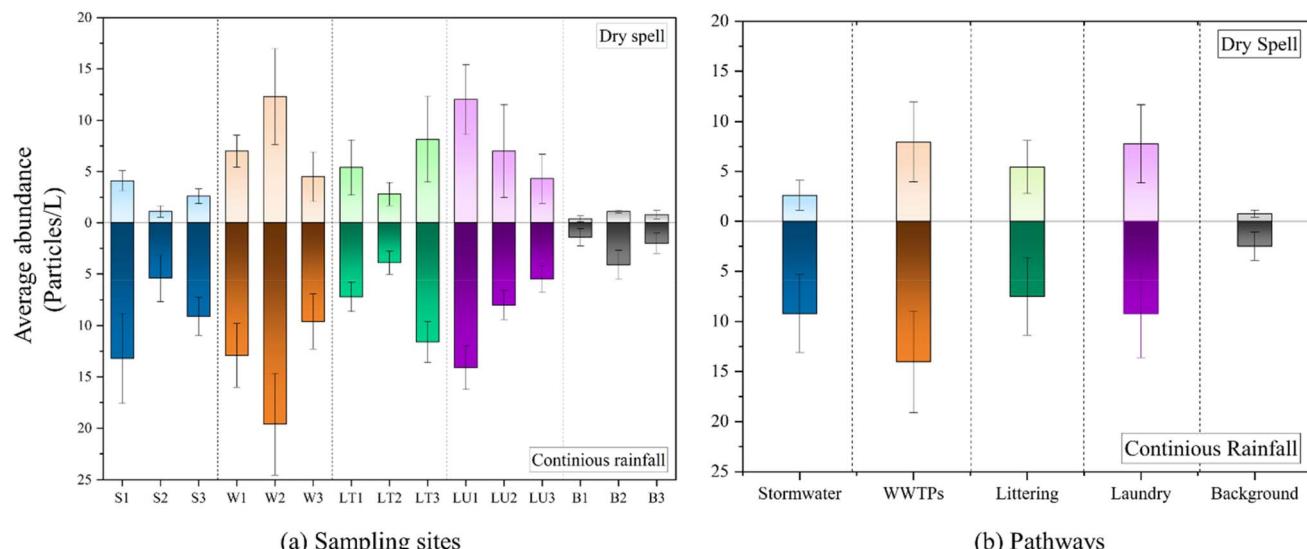


Fig. 2 Microplastic abundance at each site (a) and across pathways (b).

analytical approaches (Table S4). We observed that the range of MPs abundance observed in Dal Lake was higher than reported studies from Finland, Saimaa Lake ( $0.6\text{--}0.8 \text{ p L}^{-1}$ ),<sup>50</sup> Canada, Ontario Lake (average:  $0.8 \text{ p L}^{-1}$ ).<sup>19</sup> However, when compared with studies from Asia, the abundance was within the range observed in urban lakes, especially from developing countries. For example, MPs abundance in Renuka Lake and Kumaraswamy Lake in India ranged between ( $2\text{--}64 \text{ p L}^{-1}$ ) and ( $3.33\text{--}12.11 \text{ p L}^{-1}$ ), respectively.<sup>51,52</sup> Similarly, the MPs abundance in Rawal Lake in Pakistan ranged between ( $0.5\text{--}4.8 \text{ p L}^{-1}$ ).<sup>53</sup> The higher abundance of MPs in these countries can be attributed to a combination of factors, including inadequate waste management infrastructure, limited public awareness and education, poor legislation, finite resources, and mismanagement of waste.<sup>54</sup> Moreover, population density, tourism, and informal economic activities, particularly around urban lakes, further contribute to increased levels of MPs.<sup>55</sup>

The spatiotemporal distribution of MP concentrations from diverse pathways and under different weather conditions is shown in Fig. 2b. The persistent dominance at WWTP outlets in both weather conditions indicates their role as persistent hot-spots of MP pollution. WWTPs are estimated to emit approximately 65 million MPs per day into water bodies.<sup>56</sup> After continuous rainfall, the results are particularly critical as the concentration approximately doubled from  $7.9 \text{ p L}^{-1}$  in a dry spell to  $14.03 \text{ p L}^{-1}$  after continuous rainfall (Fig. 2b), further illuminating the vulnerability of WWTPs under hydraulic stress. Luo *et al.*<sup>41</sup> also observed similar results, with the concentration of MPs in wet weather being 1.5 times that observed in dry weather. Similarly, Uoginte *et al.*<sup>57</sup> also reported a 27% increase in MPs entering a WWTP in Lithuania during the wet season. The increased hydraulic loading during rainfall significantly reduces the retention time in treatment processes, compromising the efficiency of WWTPs.<sup>58,59</sup> Also, the higher flow velocities and turbulence can further lead to the resuspension of previously settled MPs within the treatment system,

essentially re-mobilizing particles that had been temporarily sequestered in sludge or settlement tanks.<sup>60</sup> Furthermore, the shock loading from sudden influxes of stormwater *via* combined sewers can destabilize the physical-chemical processes within treatment units,<sup>61</sup> affecting the settling process that is crucial for MP removal.<sup>62</sup> However, there is limited research on the role of combined sewer systems in influencing MP abundance within WWTPs, especially during rainfall events.

Conversely, at the stormwater outfalls, we observed a greater shift in average MP concentrations from ( $2.5 \pm 1.5 \text{ p L}^{-1}$ ) during dry weather to ( $9.2 \pm 3.9 \text{ p L}^{-1}$ ) after continuous rainfall Fig. 2b. This substantial rise likely reflects the mobilization of MPs accumulated in urban runoff and their subsequent discharge into the water body during rainfall-induced runoff events.<sup>63,64</sup> In addition, during sampling after continuous rainfall, we observed the presence of floating plastic litter, including cigarette butts, at the stormwater outfall location. Thus, building upon our prior research,<sup>48</sup> which highlighted the role of roadside littering and mismanaged waste in contributing to MP pollution *via* stormwater runoff, it is plausible that plastic litter in terrestrial environments undergoes degradation generating MPs, which subsequently gets washed away with stormwater runoff into the downstream water bodies.

Similar patterns of increased MP abundance following continuous rainfall were observed at other locations as well, indicating a widespread response to precipitation events across the study area. However, the magnitude of the increase was not as strong as observed at stormwater outfalls (Fig. 2b). This increase likely resulted from the agitation of the water-sediment interface at the bottom of the Lake due to continuous rainfall, which leads to the resuspension of immobilized MPs from sediment into the surface water. Similar findings were reported by Wu *et al.*,<sup>23</sup> where the abundance of MPs increased in surface water after persistent rainfall by 62.4%. Additionally, atmospheric wet deposition may also contribute to this increase, as



continuous rainfall can scavenge airborne MPs and introduce them directly into the surface waters. Sun *et al.*<sup>14</sup> reported that atmospheric wet deposition significantly increases MP flux compared to dry conditions (1.6–2.2 times higher). This increased washout of airborne MPs during rainfall will lead to a cumulative increase in MPs directly into surface waters. This reflects that other sampling locations may receive MP inputs from diverse sources with varying degrees of susceptibility to rainfall-induced mobilization, resulting in comparatively lower increases in MP abundance. As per our field observation, the significantly lower abundance of MPs at the background sites is likely due to the minimal anthropogenic stress, the absence of the relevant pathways, and the leading road along the periphery of the lake. This validates our hypothesis that there is a relevant association of different pathways in shaping MP abundance in aquatic environments at a catchment scale. It also raises questions about the extent to which road networks, for example, may either contribute to or mitigate MP dispersal depending on their proximity to water bodies.

## 4 Characteristic profiles of MPs across different pathways

### 4.1 Shape and color

Understanding whether some shapes of MPs are more common in specific pathways and their association with color is important for effective pollution management.<sup>65</sup> By identifying the predominant shapes in different pathways, we can trace back to specific sources and human activities contributing to their

widespread distribution.<sup>66</sup> Various shapes of MPs were observed in this study Fig. 3. Overall, during the dry spell, most MPs observed across pathways were fibers (52.8%) and fragments (34.2%), followed by films (8.4%). After continuous rainfall, fibers (56.4%) and fragments (31.2%) remained dominant, while the proportion of films decreased to 5%. Other shapes were also observed, but they accounted for less than 5% of the total MPs Fig. 4. Although there are considerable variations in MPs concentrations observed globally, there is less variation in MPs shapes reported, with fibers and fragments being the leading morphotypes identified in environmental samples globally.<sup>51</sup> Interestingly, in this study, the proportion of shapes observed across pathways showed both spatial and temporal variations Fig. 4. In dry spell, the average proportion of fragments observed near stormwater outlets was 31%, which increased to 41% after continuous rainfall. Conversely, near littering sites, the proportion of fragments decreased from 48% in dry spells to 36% after continuous rainfall. Also, black particles were predominantly observed near stormwater outfalls, which increased from 7% in dry spell to 17% after continuous rainfall Fig. 4. This aligns with higher fragments and black particles reported in stormwater samples originating from tire and road wear abrasion.<sup>67</sup> In addition, the higher dominance of fragments at stormwater outlets reflects the breakdown of larger items by UV radiation and physical wear in terrestrial environments.<sup>64</sup> Conversely, after continuous rainfall, the abundance of fibers increased near WWTP outlets. The average proportion of fibers increased from 48% in a dry spell to 60% after rainfall. Previous studies have also highlighted

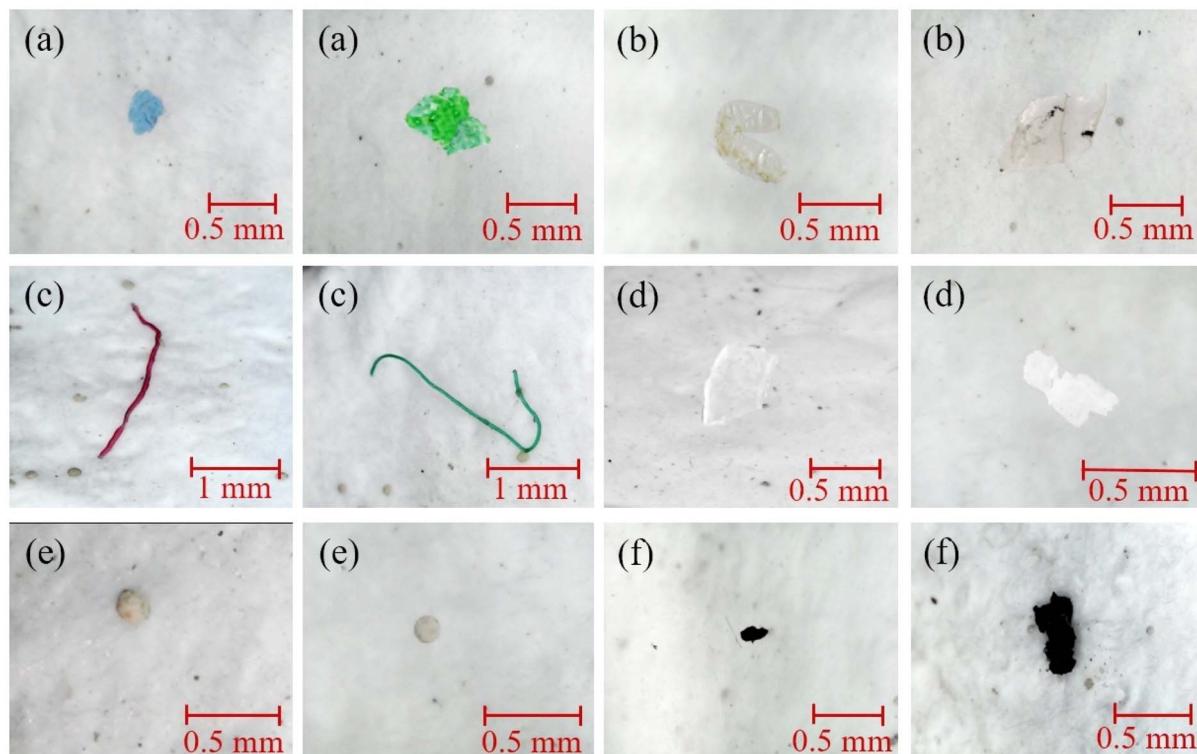


Fig. 3 Various shapes of MPs observed ((a) fragments, (b) films, (c) fibers, (d) foams, (e) pellets, (f) rubber).



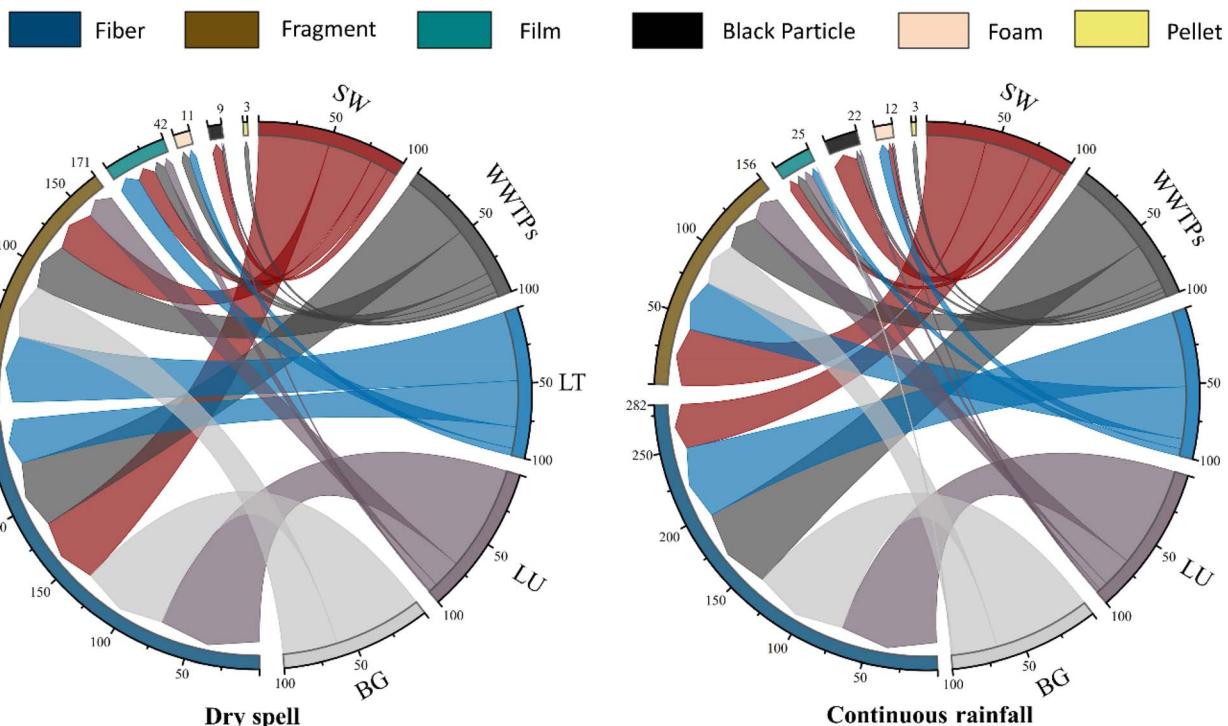


Fig. 4 Spatiotemporal variation of different shapes of MPs observed at each pathway. (SW: stormwater, WWTPs, LT: littering, LU: laundry, BG: background).

a greater prevalence of fibers in WWTP effluents during wet weather.<sup>68</sup>

Further data analysis showed a significant association between MP shapes and their respective pathways. This finding indicates that distinct pathways have characteristic MP profiles, which may reflect differences in the sources, usage patterns, environmental behavior, and transport mechanisms. For example, the abundance of fibers varied significantly among pathways ( $H = 23.71$ ,  $df = 3$ ,  $p < 0.001$ ). Specifically, the abundance of fibers near stormwater sites was significantly lower than WWTPs sites ( $p = 0.0035$ ) and laundry sites ( $p = 0.0006$ ). The high proportion of fibers at both WWTPs and laundry sites reflects the substantial contribution of synthetic textiles to MP pollution. Many previous studies have observed fibers to be the dominant shape of MPs in WWTP effluents. Franco *et al.*<sup>69</sup> reported that fibers constituted 40% of the MPs observed in WWTP effluents in Cadiz, Spain. Similarly, in India, Parashar and Hait<sup>56</sup> reported that 42% of the MPs observed in 7 WWTP effluents were fibers. In addition, other MP shapes, including films, fragments, and pellets, were observed near WWTP outlets, which reflect inputs from various residential and commercial sources, pointing to the complex role these facilities play in shaping downstream MP pollution.<sup>19</sup>

In addition, analysing the relationship between color and shape can further provide information on their environmental degradation<sup>70</sup> and potential ecological impacts, as certain colors may increase the likelihood of ingestion by aquatic organisms.<sup>71</sup> We did not find any variation in the color of MPs observed between different pathways however, black-colored

MPs were dominant in both weather conditions (dry spell: 23%; continuous rainfall: 29%); other colors in dry spell were blue (22%), transparent (19%), and red (14%). Similarly, after continuous rainfall, the proportion was transparent (20%), red (16%), and blue (14%). We also observed other colors but with relatively lesser frequency <10%, Fig. 5. Further data analysis showed a moderate association (Cramer's  $v = 0.42$ ,  $p = 0.0027$ ) between the color and shape of MPs. This suggests that specific colors and shapes co-exist in ways that reflect their origin, material properties, and environmental processing.<sup>72</sup> For example, the dominance of black and blue fibers reflects that textile-derived microfibers are prevalent in domestic and laundry effluents.<sup>19</sup> These colors highlight the types of dyes and polymers used in textiles, which are resistant to degradation, allowing them to persist in the environment and accumulate in specific shapes. The consistent presence of transparent films is mainly associated with packaging materials, further highlighting the contribution of single-use plastics to MP pollution.<sup>49</sup> More interestingly, the higher percentage of blue fragments observed in this study may indicate patterns of environmental weathering, as blue-colored plastics are known to degrade more rapidly under UV exposure due to their shorter wavelengths. This accelerated degradation can compromise structural integrity, potentially leading to faster fragmentation into smaller particles over time.<sup>73</sup> Therefore, future research should explore the correlation between color and fragmentation of MPs to help inform the design of more durable and environmentally friendly plastic products.

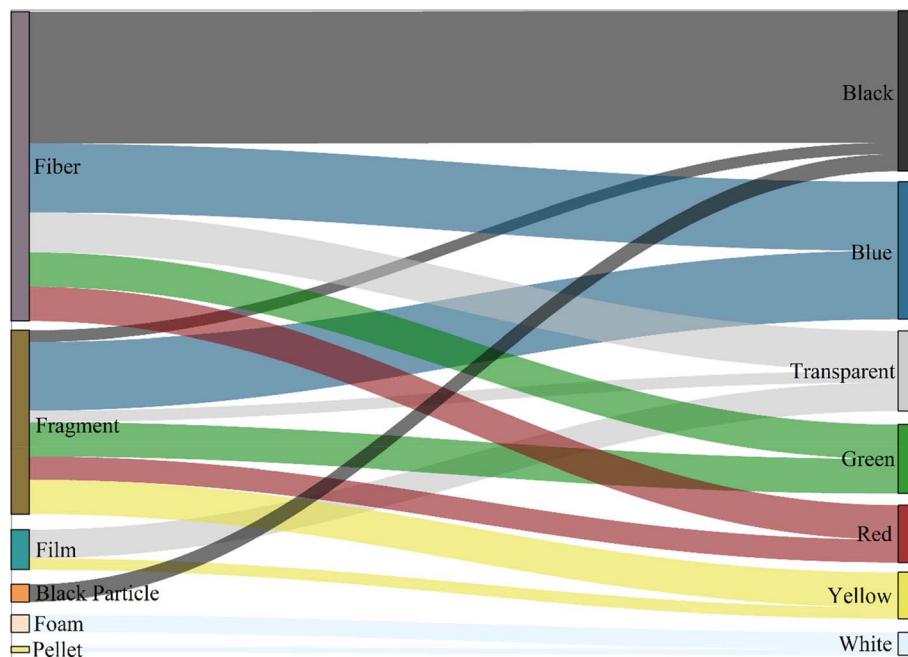


Fig. 5 Variation of shape with color of MPs observed.

## 4.2 Size distribution

The size of MPs is a key factor influencing various processes, including their movement through the water column, their tendency to settle or disperse, and their interactions with aquatic species.<sup>74</sup> Across all pathways, small MPs (<500 µm) dominated, accounting for 55% and 44% in dry spell and continuous rainfall, respectively. We also observed an increase in MP abundance as the particle size decreased. These results are comparable with previous studies reporting that most of the MPs found in the water matrix are smaller than 1 mm and increase with a decrease in size.<sup>75,76</sup> This size range is particularly concerning as it poses a significant risk to aquatic

organisms due to their comparable size to food items, which are easily mistaken and ingested by various aquatic species.<sup>77</sup> There were no variations in the MP size range observed across different pathways and weather conditions. However, the proportion of the larger particles (>500 µm) increased after continuous rainfall, especially at the stormwater outlet (Fig. 6). This can be attributed to the limited degradation rate of MPs during the period of continuous rainfall as opposed to a dry spell. Zhang *et al.*<sup>49</sup> also reported similar results, where in wet weather, the size of MPs particles increased in the stormwater samples compared to dry weather. In addition, the persistent rain likely results in scouring the sediment layers, mobilizing

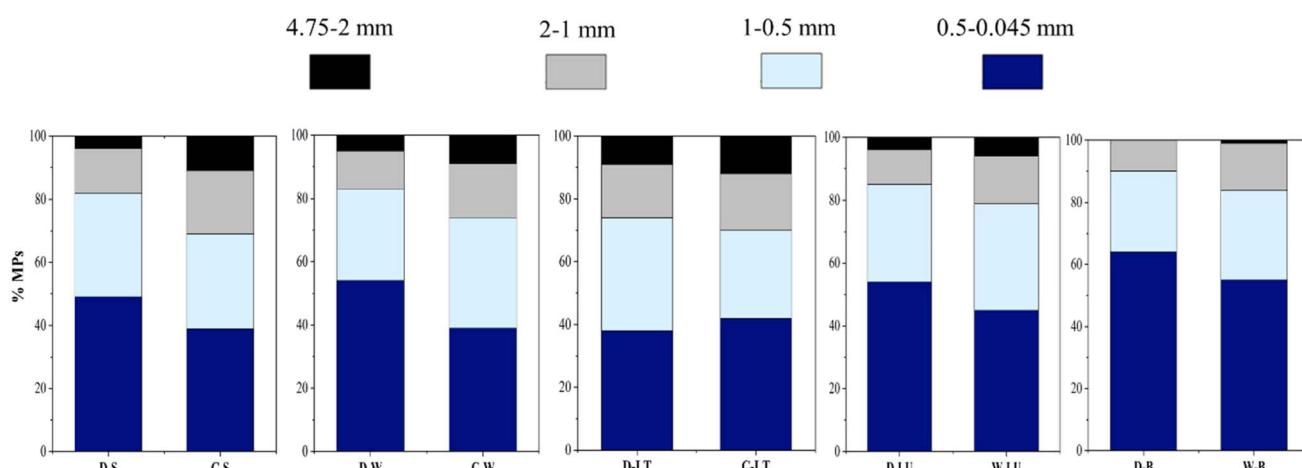


Fig. 6 Size distribution observed across different pathways and weather conditions. (DS: stormwater dry, CS: stormwater rainfall; DW: WWTPs dry, CW: WWTPs rainfall; DLT: littering dry, CLT: littering rainfall; DLU: laundry dry, WLU: laundry rainfall; DB: background dry, WB: background rainfall).



larger MPs that had settled over time, resulting in their increased presence in the water column. Wu *et al.*<sup>23</sup> reported that after persistent rainfall, there was an increase in larger size MPs in surface water and a subsequent decrease in sediments. Similarly, Sang *et al.*<sup>78</sup> also observed that there was an increase in the size of MPs observed in the runoff after heavy rainfall due to the resuspension of previously deposited MPs in the sediments of the stormwater canal. These findings highlight that, under specific weather conditions, sediments can act as sources of MPs within aquatic ecosystems. This dual role further complicates our understanding of MPs fate and transport in aquatic systems and emphasizes the importance of accounting for hydrodynamic disturbances in future MPs studies.

#### 4.3 Polymer characteristics

A total of 9 MP polymers were observed across pathways using ATR-FTIR, Fig. S2. Although the polymer profiles of MPs showed spatiotemporal differences, we observed that polyethylene (PE) and polypropylene (PP) were widely distributed except at laundry sites, where the dominant MPs observed were polyethylene terephthalate (PET) and polyamide (PA), as shown in Fig. 7. The spatial distribution showed that more than 60% of the particles observed near stormwater and littering sites were PP and PE. These findings are not surprising given the widespread use of PE and PP in consumer products, packaging, and household applications.<sup>79</sup> In addition, the ubiquitous presence of PE and PP across pathways can also be attributed to their physical characteristics. Both PE ( $0.92 \text{ g cm}^{-3}$ ) and PP ( $0.96 \text{ g cm}^{-3}$ ) have lower densities than water, making them more likely to float in aquatic systems.<sup>48</sup> Additionally, their widespread use in single-use items like food packaging, bottles, and bags increases their likelihood of entering the environment through littering and eventually reaching surface waters.<sup>80</sup> Interestingly, the distinct polymer signature at laundry sites was dominated by PET and PA fibers Fig. 7. We also observed natural fibers, mainly cotton, at laundry sites, but these were excluded to prevent false estimation of MPs. This finding is particularly important as it highlights the substantial

contribution of textile fabrics to MP pollution through everyday washing activities. Conversely, near WWTP sites, the fibers were predominantly synthetic in nature, indicating that these facilities may preferentially retain or degrade natural fibers more effectively. Compared to natural fibers, synthetic fibers are durable and more resistant to degradation and may persist through treatment systems and, therefore, are discharged into receiving water bodies.<sup>81</sup> Previous studies have also reported a higher percentage of PET fibers in freshwater systems with WWTP effluents as an important pathway.<sup>82,83</sup> While both synthetic and natural fibers have been reported in numerous studies, with the latter being highly underrepresented as a result, our understanding of their fate in freshwater systems remains limited. Natural fibers, often considered biodegradable, may still persist longer in aquatic ecosystems when chemically treated, dyed, or exposed to certain conditions.<sup>84</sup> Chen and Jakes.<sup>85</sup> reported that a recovered dyed cotton coat showed no significant degradation despite being submerged in the ocean for 131 years. From the perspective of the temporal distribution, we observe some shifts in MP composition after continuous rainfall (Fig. 7). For example, after continuous rainfall, the percentage of PET fibers increased from 15% to 28% at WWTPs and 19% to 36% at laundry sites. One plausible explanation can be the density-related segregation of MPs in the water column, where heavier particles are more susceptible to settling.<sup>86</sup> The density of PET ( $1.37\text{--}1.46 \text{ g cm}^{-3}$ ) is higher and therefore settles faster compared to other polymers. Many studies have reported an increased percentage of PET in the sediments compared to the surface water.<sup>16,87</sup> However, during continuous rainfall, the increased turbulence in the water column creates high-energy conditions that may resuspend previously settled high-density MPs, such as PET, back into the surface water.<sup>88</sup>

It is important to highlight here that density alone cannot be the principal reason for the lower abundance of high-density polymers in the dry spell. Other properties, especially the size of MPs and various external factors like the degree of weathering, biofouling, and surface water dynamics, can also contribute to the settling of MPs in freshwater systems.<sup>89</sup> Interestingly, continuous rainfall not only altered the polymer distribution but also led to the appearance of new polymers, particularly near stormwater outlets (Fig. 7). Like polyurethane (PU), acrylonitrile butadiene styrene (ABS), and polyvinyl chloride (PVC), are often associated with road dust originating from tire and road wear abrasions.<sup>90</sup> In addition, PU and ABS are common polymers used in the shoe industry,<sup>91</sup> which further reflects the role of footfall due to high tourism flow in the study area as an important source. The polymer-specific patterns observed with respect to each pathway and weather condition in this study highlight the complexity associated with source identification. More importantly, this study further illuminates that once MPs enter freshwater systems, they don't remain there as static particles but are actively mobile in response to changes in weather conditions. As climate change potentially alters precipitation patterns, these polymer mobility dynamics may become even more complex. Increased rainfall variability could dramatically influence MP transport mechanisms, creating new

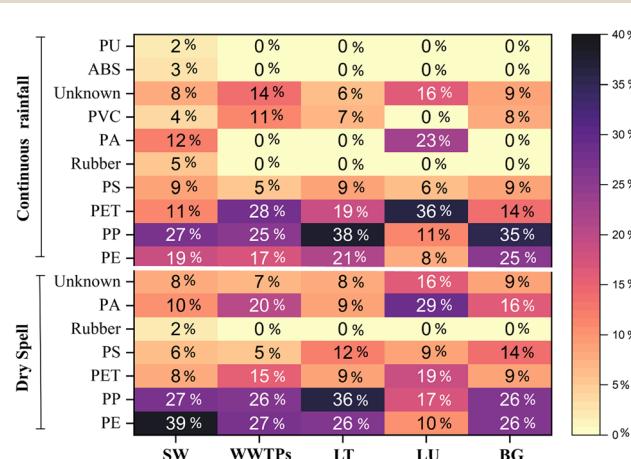


Fig. 7 Spatiotemporal variation of various polymers observed at each pathway.



environmental challenges that require sophisticated monitoring and adaptive upstream management approaches to protect aquatic ecosystems from episodic contamination events.

#### 4.4 Effect of continuous rainfall on the diversity of MPs

As the continuous rainfall influenced the characteristics of MPs at each pathway, we calculated MPDII based on Shannon's diversity index using the characteristics of polymer, shape, size, and color of MPs to better understand this complexity for identifying potential sources. Differences in Simpson indices and MPDII were observed in MP polymer, shape, size, and color across different pathways and weather conditions Fig. 8. In general, both SDI and MPDII values increased after continuous rainfall, highlighting that continuous rainfall introduces greater complexity to MP diversity. Similar findings were reported by Wei *et al.*,<sup>40</sup> where rainfall increased the diversity of MPs in surface water. In this study, particularly, the MPDII value was higher near stormwater outlets after continuous rainfall (0.74) compared to dry spell (0.68), illuminating the role of rainfall in mobilizing MPs from diverse upstream sources. Therefore, precipitation, particularly rainfall-induced runoff, facilitates the transport of land-based pollution sources to aquatic systems, as seen in previous studies where hydrological processes redistributed MPs diversity.<sup>92</sup> However, the increase in diversity after continuous rainfall further challenges the traditional single-pathway conceptual models of MP transport,

indicating a more complex interaction between weather conditions and MP mobilization mechanisms. Conversely, littering sites showed high MPDII values in dry spell (0.72) compared to continuous rainfall (0.68) this pattern likely reflects that littering sites experience localized accumulation of MPs, therefore creating distinct "hotspots" of MP pollution, where the contributions from the breakdown of plastic litter are more obvious in a dry spell, leading to higher diversity indices. The lower MPDII value after continuous rainfall may be because continuous rainfall acts as a dispersive force, washing away deposited plastic litter and redistributing them downstream across a broader area, which reflects that the MP profile is shaped predominantly by the background MP signature, suggesting that active point sources significantly contribute to the complexity of MP diversity at the site. This finding aligns with recent studies indicating that diversity indices can serve as sensitive indicators of active pollution sources rather than just accumulated contamination.<sup>93</sup> Moreover, we observed consistently lower diversity indices at the background site Fig. 8. This difference validates our methodology and suggests that MP diversity could serve as a more robust indicator of anthropogenic influence than traditional abundance measurements.<sup>24</sup>

The SDI values for polymer, shape, size, and color provided further details on these findings. In general, polymer and color characteristics were the most predominant contributors to the integrated MP diversity index. In the dry spell, the high MPDII values, were observed especially near stormwater (0.65) and

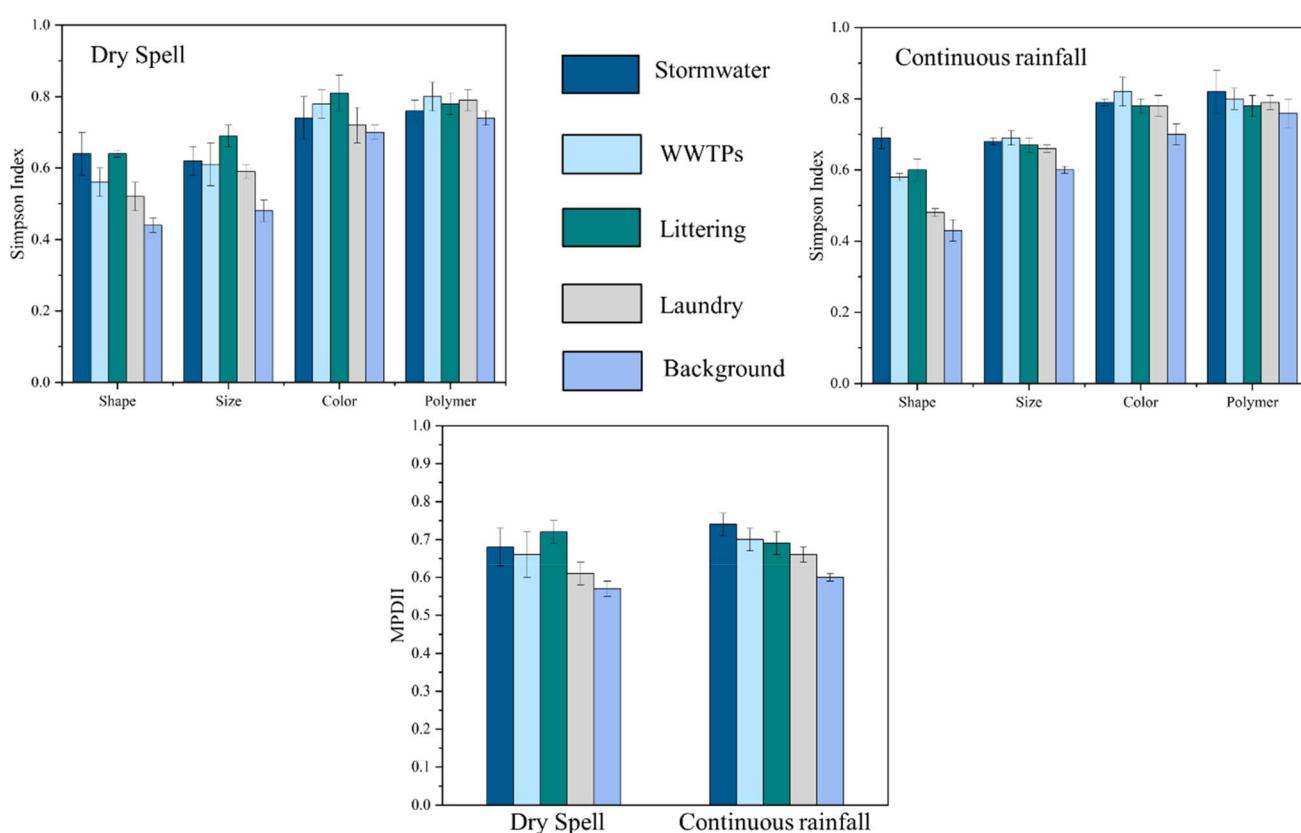


Fig. 8 Diversity indices at each pathway.



littering (0.70) sites. However, after rainfall, the MPDI increased near the stormwater sites (0.72), while it decreased near the littering sites (0.60). This highlights the transformative role of rainfall in redistributing MPs and reshaping their community structure by introducing contributions from diverse upstream sources.<sup>94</sup> This comprehensive analysis of diversity components provides a foundation for a better understanding of the temporal dynamics of MP pollution and highlights the importance of considering multiple characteristics when assessing MP contamination patterns. The increased diversity during wet conditions indicates that current MP loading estimates, often based on dry-weather sampling, may underestimate the quantity and complexity of MP pollution. This observation suggests the need for weather-stratified monitoring approaches to capture the full spectrum of MP pollution dynamics.

#### 4.5 Pathway-specific risk assessment

PLI and PRI are essential for evaluating the risks of plastic pollution in the environment. They measure the extent of pollution and its potential hazards using different indicators, offering a basis for developing effective mitigation strategies. The pathway-specific risk assessment showed complex shifts in MP pollution patterns, with important variations driven by weather conditions (Table 1). At stormwater outlets, the sharp rise in PRI from 66.3 (low risk) during dry spells to 494.9 (considerable risk) after continuous rainfall is driven by an increase in polymer hazard index values (HI) from 11.34 to 80.05, despite relatively stable PLI values. This substantial shift suggests that stormwater runoffs potentially concentrate high-risk polymers through urban landscapes like PVC, PU, and ABS, as observed in this study Fig. 7. Such an increase in polymer hazard indicates that these pathways are more likely to transport more toxic polymer types, possibly due to their physicochemical properties influencing their mobility during continuous rainfall.<sup>48</sup> Conversely, the relatively stable moderate PRI values Table 1 near WWTP outlets suggest that these facilities act as consistent concentrators of both MP abundance and hazardous polymer types. The decline in PLI values from 18.22 in dry spell to 9.59 after continuous rainfall indicates a dilution effect attributable to increased flow rates during continuous rainfall. However, the increase in HI value (12.67 to

17.7) suggests the persistence of toxic polymers even under hydrological changes. This pattern raises critical questions about the efficiency of conventional wastewater treatment systems in managing downstream MP pollution risk, particularly during change in weather conditions. At littering sites, PRI values decreased from 113.6 during dry spell to 44.7 after continuous rainfall. Similar trend was observed near laundry sites where PRI values decreased from 226.7 during dry spell to 64.6 after continuous rainfall. This can be attributed to the fact that continuous rainfall may have redistributed MPs away from the local point sources. However, the displacement of MPs from these localized hotspots will result in downstream accumulation, raising concerns about their cumulative risks in receiving water bodies.<sup>40</sup> Background sites with consistently low PRI values (21.20 during the dry spell and 17.21 after rainfall). The minimal changes in HI (11.62 to 10.68) and PLI (1.76 to 1.61), reflects minimal anthropogenic influence but highlights the pervasive nature of MPs, and their capacity to infiltrate less-disturbed ecosystems.

These findings inform how changes in weather conditions significantly influence MP pollution dynamics, with continuous rainfall serving as a principal catalyst for redistribution and increased toxicity risk. The prevalence of extremely hazardous polymers, such as PVC, PU, and PS, highlights the urgent need for improved policies that tackle MP abundance and chemical composition. Interventions adapted to specific pathways, such as improved treatment technology for WWTPs, enhanced stormwater treatment systems to capture MPs before they reach downstream waterbodies, and more stringent regulations on high-risk polymers, are crucial for addressing the environmental threat caused by MPs in aquatic ecosystems.

## 5 Limitations of the study

While this study has provided significant findings, several limitations must be noted. First, the sampling methods and analysis are still up for debate and are subject to uncertainties.<sup>95,96</sup> This study involved composite grab sampling, though representative, but still provides limited temporal resolution and might not have provided a full spectrum of the MP's abundance in both weather conditions. Future studies should consider long-term monitoring to better account for temporal fluctuations in MP inputs. Second, while the study used well-established and standard procedures for MPs identification and characterization, there are still some limitations inherent to the visual sorting and FTIR-based characterization, which may have underestimated the results, especially when it comes to small-sized MPs with preferred dimensions <500 µm. Third, although this study used zinc chloride for density separation for isolating high-density MPs, its toxicity and potential reactivity may have limitations for large-scale and environmentally sensitive applications. In future studies, sodium iodide (NaI) may be preferred as a less toxic alternative, particularly for facilitating safer handling and disposal. Additionally, due to the study's focus on highly urbanized lakes, some details might not be comparable to other lacustrine ecosystems due to the difference in geographical and

**Table 1** Risk assessment of MPs across pathways in different weather conditions

Pathway	Weather condition	HI	PLI	PRI
Stormwater	Dry spell	11.34	5.67	66.3
	Continuous rainfall	80.05	6.18	494.9
WWTPs	Dry spell	12.67	18.22	239.8
	Continuous rainfall	17.7	9.59	170.25
Littering	Dry spell	10.22	12.41	113.61
	Continuous rainfall	9.1	4.91	44.7
Laundry	Dry spell	14.23	17.80	265.74
	Continuous rainfall	10.61	6.09	64.68
Background	Dry spell	11.62	1.76	21.20
	Continuous rainfall	10.68	1.61	17.21



hydrological conditions. Lastly, the choice of the diversity indices and risk assessment framework used in this study offers a satisfactory picture of the problem, but it presupposes certain hazard characteristics of the polymer, which may not reflect the actual interaction of MPs with the environment or the long-term impact of MP pollution on the ecosystem. As such, improving the methodological approaches and managing these limitations will be crucial in future studies for expanding the knowledge base on MPs pollution and associated risks in freshwater systems.

## 6 Conclusion and future prospects

Addressing the MP challenge necessitates collecting reliable, localized data to inform solutions and establish meaningful compliance targets. This study comprehensively provides an integrated assessment of MP pollution in an urban lake system, highlighting a pathway-specific approach under different weather conditions (dry spell and continuous rainfall). By evaluating four distinct pathways, WWTPs, stormwater runoff, laundry discharges, and littering zones, our findings highlight the spatial heterogeneity of MPs, with significant differences observed between dry spell and continuous rainfall. Continuous rainfall changed lake hydrodynamics, which resulted in an increase in MP abundance across all pathways, particularly near stormwater and WWTP outlets. The pathway-specific approach used in this study showed that different pathways have characteristic MP profiles, which may reflect their differences in the sources, usage patterns, environmental behavior, and transport mechanisms. For example, the dominance of black and blue fibers near laundry sites observed reflects that textile-derived MPs are prevalent in domestic use. This study also spotlighted that continuous rainfall also changes polymer distribution in surface waters, resulting in the appearance of new polymers like PVC, PU, and ABS, particularly near stormwater outlets. Further, using diversity indices and a comprehensive risk assessment approach, this study highlights delicate relationships between various sources and MP accumulation patterns. Continuous rainfall also influenced the diversity and risk of MPs, reshaping their characteristics and increasing toxicity levels. The increase in MPDII values at stormwater outlets (0.66 to 0.72) highlights the critical role of rainfall-induced runoff in mobilizing MPs from diverse upstream sources, whereas the decrease at littering sites (0.70 to 0.66) reflects the reduced contribution from active point sources during wet conditions. The high risk of toxic polymer accumulation near stormwater runoff reinforces the importance of improving infrastructure, such as enhanced stormwater management and improved urban planning, including developing more pervious pavements, to reduce MP influx into sensitive ecosystems, especially in densely populated areas. This study contributes to global microplastic research by providing an informed analysis of multiple MP pathways in a high-altitude urban lake, an overlooked region despite increasing urbanization and ecological sensitivity.

Future monitoring studies should consider stratifying data collection, not just limited to seasonal variations, but should

investigate extreme weather-induced variabilities, especially the impacts of continuous rainfall, floods, and extended dry spells on MP dynamics. Such an approach will provide more comprehensive information on the fluctuations of MP concentrations across different environmental compartments, allowing more effective pollution management during extreme weather events. As the sources of MP pollution are often linked to local human activities such as littering and laundering, there is a significant need for local public awareness and regulations that must account for informal waste leakage and decentralized effluent discharges. Furthermore, understanding the environmental persistence, toxicity, and bioaccumulation potential of different polymer types will be essential in developing regulations and policies to reduce their release into the environment.

## Author contributions

Mozim Shafi: conceptualization, methodology, sampling and experiments, data analysis, visualization, and writing – original draft. Ayan Lodh, Reyaz Hussain Akhoon: methodology, sampling, and experiments. Khalid Muzamil Gani: conceptualization, resources, formal analysis, writing – reviewing, editing, supervision. Sudha Goel: conceptualization, resources, formal analysis, writing – review & editing, supervision.

## Conflicts of interest

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

## Data availability

The datasets used or analyzed in this study are available from the corresponding author on reasonable request. Supplementary information is available. See DOI: <https://doi.org/10.1039/d5va00201j>.

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