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EDITED BY
Surya Singh,
ICMR-National Institute for Research in Environmental Health, India

REVIEWED BY
Tarik Bahaj,
Mohammed V University, Morocco
Jacinto Elías Sedeño-Díaz,
Coordinación Politécnica para la Sustentabilidad, Instituto Politécnico Nacional (IPN), Mexico
Maria Romina Alvarez Troncoso,
Faculty of Biology, University of Vigo, Spain

*CORRESPONDENCE
Pegah Jahanpeyma
pegah.jahanpeyma@edu.bme.hu

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Quantitative and qualitative analysis of microplastic pollution in a large European river

Pegah Jahanpeyma[1,2]*, Flóra Pomázi[1,2], Alexander Anatol Ermilov[1,2], Anna Szöllosi[1], Dániel Gere[3], Andrea Toldy[3,4] and Sándor Baranya[1,2]

[1]Department of Hydraulic and Water Resources Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, Hungary, [2]National Laboratory for Water Science and Security, Department of Hydraulic and Water Resources Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, Hungary, [3]Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest, Hungary, [4]MTA-BME Lendület Sustainable Polymers Research Group, Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest, Hungary

Introduction: Microplastic pollution consists of plastic particles smaller than 5 mm, originating from the fragmentation of larger plastic debris due to processes such as ultraviolet radiation, as well as from primary sources including industrial plastic pellets. These particles are widely transported across atmospheric, aquatic, and terrestrial systems and pose significant environmental and health risks to flora, fauna, and humans. Rivers play a critical role in conveying microplastics to aquatic environments. This study investigates microplastic pollution in the Hungarian section (Budapest reach) of the Danube River, Europe's second-largest river and a vital water resource for the region.

Methods: Water samples were collected across different depths of the water column using a Multilevel Manta net. Laboratory analyses were performed using Fourier-transform infrared (FTIR) spectroscopy and digital microscopy for polymer identification and particle characterization. Concurrent flow measurements were conducted to estimate microplastic mass flux rates.

Results: The average microplastic concentration was 0.311 mg/m^3 (142 particles/m^3). The most abundant polymers were polystyrene, polyethylene, and polypropylene. Detected particles occurred in various forms, including fragments, foam, and flakes, and exhibited colors such as yellow, black, gray, and green. These findings indicate substantial microplastic contamination in the studied reach of the Danube River.

Discussion: The results highlight the Danube River's role as a significant transport pathway for microplastics and underscore the need for targeted monitoring and mitigation strategies. This study contributes to understanding microplastic dynamics in large European rivers and provides valuable insights for developing effective pollution control and management approaches.

KEYWORDS
microplastic characterization, microplastic identification, microplastic pollution, microplastics, plastic pollution, riverine microplastics

1 Introduction

Global plastic production continues to rise sharply, reaching an estimated 413.8 million tons in 2023 and projected to surpass 460 million tons by Plastics Europe (2024). However, inadequate waste management and limited recycling capacity have led to large quantities of persistent plastics accumulating in the environment. Exposure to ultraviolet (UV) radiation, mechanical abrasion, chemical and microbial activity, and hydrodynamic forces gradually fragments this debris, generating microplastics (MPs), typically defined as particles <5 mm (Derraik, 2002; Kutz, 2002; Moore, 2008; Barnes et al., 2009; Hopewell et al., 2009; NOAA-Marine Debris Program, 2009; Rios et al., 2010; Andrady, 2011; Browne et al., 2011; Cole et al., 2011; Roy et al., 2011; Jahanpeyma and Baranya, 2024). MPs occur across atmospheric, terrestrial, and aquatic systems and can be transported through rivers, wind, runoff, and wastewater, increasing the likelihood of exposure to organisms and humans. Their growing prevalence has been linked to ecological disruption and a range of health risks (Crawford et al., 2017; Waldschläger et al., 2020).

Rivers are central to the mobilization of MPs, acting both as major conduits to marine environments and as temporary storage zones where particles settle, accumulate, and can later be remobilized. Global estimates suggest that river systems deliver up to 80% of the MPs entering the oceans ($0.41–4 \times 10^{6}$ton annually) (Horton et al., 2017; Liedermann et al., 2018; Campanale et al., 2020; Adomat and Grischek, 2021; He et al., 2021; Pojar et al., 2021). Consequently, oceans now contain notable MP loads, including high concentrations of microfibers, with the Arctic emerging as a significant accumulation zone (Lima et al., 2021). The movement and fate of MPs differ markedly from those of natural sediments due to their diverse polymer densities, morphologies, and surface alterations, such as biofilm formation. Hydrological processes, including flow velocity, turbulence, salinity, seasonal discharge, and geomorphology, further shape transport and deposition patterns (Kaiser et al., 2017; Alfonso et al., 2021). Low-density polymers, such as polyethylene (PE) and polypropylene (PP), tend to remain buoyant and travel long distances, whereas denser polymers [e.g., Polyamide (PA), Polyethylene terephthalate (PET)] accumulate closer to their source areas. Enhanced flows can resuspend previously deposited MPs, whose critical shear stress thresholds differ substantially from those of mineral sediments (Ballent et al., 2016; Nel et al., 2018; Porter et al., 2018; Waldschläger and Schüttrumpf, 2019; Liro et al., 2020; Waldschläger et al., 2020; He et al., 2021).

Understanding MP distribution requires methodologies tailored to their atypical transport behavior. Common approaches include bulk water sampling, the use of nets with mesh sizes ranging from 60 to 100 μm, *in-situ* filtration, and submersible pump systems. Studies suggest that combining bulk and net techniques provides a more representative picture of vertical MP distribution within the water column (Liu et al., 2020). In marine contexts, manta, neuston, or plankton nets (with a mesh size of 0.1–0.3 mm) are routinely employed; however, variations in mesh size, sampling depth, and tow speed can introduce significant biases and may underestimate smaller or more flexible particle types, such as fibers (Obbard, 2018).

Numerous reviews focusing on European riverine systems highlight substantial heterogeneity in sampling strategies, polymer identification methods, and spatial patterns of MP contamination (Hidalgo-Ruz et al., 2012; Rocchia et al., 2017; Jahanpeyma and Baranya, 2024). In the Antuã River (Portugal), water and sediment samples were collected at three sites along an upstream–downstream gradient, including São João da Madeira, Aguincheira, and Estarreja, during two sampling campaigns conducted in March and October 2016. The selected sites represented contrasting population densities and land-use characteristics, encompassing urban and industrial areas as well as locations near wastewater treatment plant (WWTP) discharges, particularly the Salgueiro WWTP. MP concentrations in surface waters ranged from 5 to 51.7 mg m^{-3} (58–1265 particles m^{-3}), while sediment concentrations varied between 2.6 and 71.4 mg kg^{-1} (18–629 particles kg^{-1}). Spatial variability in MP abundance was strongly influenced by local hydrodynamic conditions and anthropogenic pressures, with PE and PP dominating the polymer composition as confirmed by FTIR analysis (Rodrigues et al., 2018). In Spain (Ría de Vigo), manta-net surveys (using a 300 μm mesh) combined with two-dimensional hydrodynamic modeling showed a preferential capture of pellets and fragments compared to fibers, highlighting a methodological bias (Díez-Minguito et al., 2020). Estuaries such as the Guadalquivir exhibit strong discharge variability, from <40 m^3/s in low-flow periods to >400 m^3/s during floods, while the Ría de Vigo displays relatively low MP levels (0.041–0.2 particles/m^3), again dominated by PE (Bermúdez et al., 2021).

The Danube River, Europe's second longest, is a major source of plastics entering the Black Sea. Estimated daily fluxes approach 4.2 ton, with annual loads exceeding 1,500 ton (Lechner et al., 2014). However, MP transport along the Danube is modulated by extensive hydropower development, channelization, and floodplain regulation, which have collectively reduced sediment fluxes by −60% (Habersack et al., 2016; Pojar et al., 2021). These alterations promote the trapping of MPs within impounded reaches and floodplain deposits (Habersack et al., 2016; Pojar et al., 2021). In the Black Sea, low-density polymers remain widely dispersed in surface waters, whereas heavier polymers and fibers accumulate in coastal and deltaic sediments (Habersack et al., 2016; Pojar et al., 2021). These patterns highlight the combined impact of local sources and hydrodynamic regulation on MP fate across the Danube–Black Sea continuum. Figure 1 summarizes published MP concentrations and transport along the Danube River, highlighting strong longitudinal variability from its Alpine headwaters to the Black Sea (Lechner et al., 2014; Habersack et al., 2016; Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019; Kiss et al., 2021; Pojar et al., 2021; Savuca et al., 2022). Surface-water concentrations near Vienna average −17 particles/m^3 (≈41 ton/year) (Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019), increasing to −45–55 particles/m^3 across the Budapest metropolitan reach, where localized deposition at Csepel Island reaches −6 ton/year (Interreg Danube Transnational Programme, 2019; Kiss et al., 2021). Downstream of the Iron Gates dams, sediment MP levels rise sharply (≈approximately 87 particles/kg upstream, increasing immediately below the dam) before declining again (Pojar et al., 2021). In the Danube Delta, sediment concentrations peak around 620–630 particles/kg in the

Sulina and Sfântu Gheorghe distributaries, while coastal averages are −98 particles/kg with lower values in the Bulgarian sector (Pojar et al., 2021). Overall, the Danube discharges an estimated 4.2 ton of plastic/day (−1533 ton/year) into the Black Sea, with riverine sediment concentrations ranging from 10 to over 6,000 particles/kg (Lechner et al., 2014; Pojar et al., 2021). These patterns illustrate how hydrology, urban inputs, and damming influence the distribution of MP along Europe's second-longest river (Lechner et al., 2014; Habersack et al., 2016; Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019; Kiss et al., 2021; Pojar et al., 2021; Savuca et al., 2022).

Liedermann et al. (2018) introduced a Multilevel Manta (MLM) net system (with different net mesh sizes, 41 μm, 250 μm, and 500 μm) for sampling MPs across different depths of the Austrian Danube, demonstrating that vertical and lateral variability strongly affects transport estimates and that surface-only trawls can under- or overestimate MP loads by up to a factor of 30 (Liedermann et al., 2018). Inspired by this approach, we developed a customized MLM net sampler specifically adapted to the hydrodynamic conditions of the Hungarian section of the Danube River. Our design retained the core principle of simultaneous depth sampling but employed modified frame geometry and finer mesh sizes to improve stability and particle recovery under local flow conditions. These adjustments enabled a detailed, quantitative, and qualitative assessment of MPs in a highly urbanized river reach, thereby extending the applicability of MLM net sampling to different environmental and hydraulic contexts. Downstream, studies in Romania identified 6,407 MP particles/kg in sediments, dominated by PE, PP, and polystyrene (PS) (Pojar et al., 2021). Investigations in the Hungarian reach employed a customized pump-based sampler with fine mesh filters (15–100 μm), revealing multiple polymer types including PE, PP, PS, polytetrafluoroethylene (PTFE), polyacrylate (PAA), and polyester (PES), with PE, PP, and PS again most prevalent (Bordós, 2021). A further study across the Danube basin, using sedimentation boxes, quantified polymer concentrations of 22.24 μg/mg for PE, 3.23 μg/mg for PS, and lower values for other polymers. Additionally, several materials, such as PLA and natural rubber, were found to be below the detection limits (Braun et al., 2022). These studies show that while PE and PP consistently dominate riverine MP assemblages.

Reported MP concentration (C_{MP}) varies widely across studies, reflecting differences in local conditions and methodological approaches. This highlights the need for standardized protocols and for adapting sampling strategies to hydrodynamic settings, principles that guided the present investigation in the Hungarian section of the Danube River. Despite growing research on riverine MPs, studies focusing on the Danube River remain limited and unevenly distributed. Most have concentrated on upstream or downstream stretches or have provided generalized data lacking spatial and temporal detail. By contrast, the Hungarian section, which flows through Budapest and is strongly influenced by wastewater treatment plant (WWTP) effluents, industrial inputs, and complex hydrodynamics, remains understudied. Addressing this gap, the current study undertakes detailed sampling and analysis of MPs in this reach of the river. We provide quantitative and qualitative insights into MP pollution using a customized Multilevel Manta net device combined with FTIR spectroscopy. The findings advance understanding of MP dynamics in large European rivers and offer an evidence base to inform mitigation strategies at local and regional scales.

2 Materials and methods

Two sampling campaigns were conducted during summer low-flow conditions (August 2022 and August 2023) to characterize the vertical and lateral distribution of MPs under near-steady hydrological conditions. In addition, two complementary campaigns were conducted in winter 2023 to examine how variations in discharge influence C_{MP} and transport, with particular focus on discharge-driven mobilization processes.

2.1 Field sampling

Two cross-sections of the Danube River Right bank: 47° 27' 33.1"N 19° 03' 32.0" E, to Left bank: 47° 27' 27.3" N 19° 03' 46.1" E) and 1,640 + 000 river km, (Right bank: 47° 26' 35.9" N 19° 02' 58.8" E to Left bank: 47° 26' 34.7" N 19° 03' 16.3" E); Figure 2, right) were selected for sampling. Their proximity to the local central Budapest WWTP and the Budapest urban area (47° 27' 23.3" N 19° 04' 13.1" E), and their suitability for safely positioning equipment along a busy navigation route, made them ideal study sites. At each cross-section, three water columns were sampled: one along the thalweg and two near the riverbanks.

Water samples were collected using an MLM net designed at the Budapest University of Technology and Economics, following the approach of Liedermann et al. (2018). The system comprises three Manta nets arranged vertically in a water column, enabling simultaneous sampling of the near-surface, mid-depth, and near-bed layers. Each net has a 0.6 m × 0.6 m frame and a 1.5 m polyamide (PA) cone with a 500 μm mesh, which funnels particles into a Polyvinyl chloride (PVC) container fitted with matching mesh. This setup enables the capture of MPs ranging from 500 μm to 5 mm (Figure 3).

To minimize contamination, the Manta nets were thermally sealed along their edges prior to deployment, preventing the release of net-derived fibers into the samples. Equipment-specific contamination was assessed through pre-field control tests, during which each net was flushed three times with high-pressure water, and the terminal sections were inspected. No fiber release or contamination was detected in these tests. All sample collection and storage containers were similarly cleaned and verified through blank analyses, which confirmed the absence of MP contamination (especially, 5 mm to 500 μm in size). Together, these quality-control measures ensured that the samples were not affected by procedural or equipment-related artifacts.

The sampling campaign was designed to capture cross-sectional variability in MP concentrations under near-steady hydrological conditions. Field measurements were taken on a single day, when the flow and discharge conditions remained relatively constant. Due to logistical challenges in deploying MLM nets and the need to maintain a stable hydrological regime, sampling was restricted to two representative cross-sections along the Hungarian segment of the Danube River,

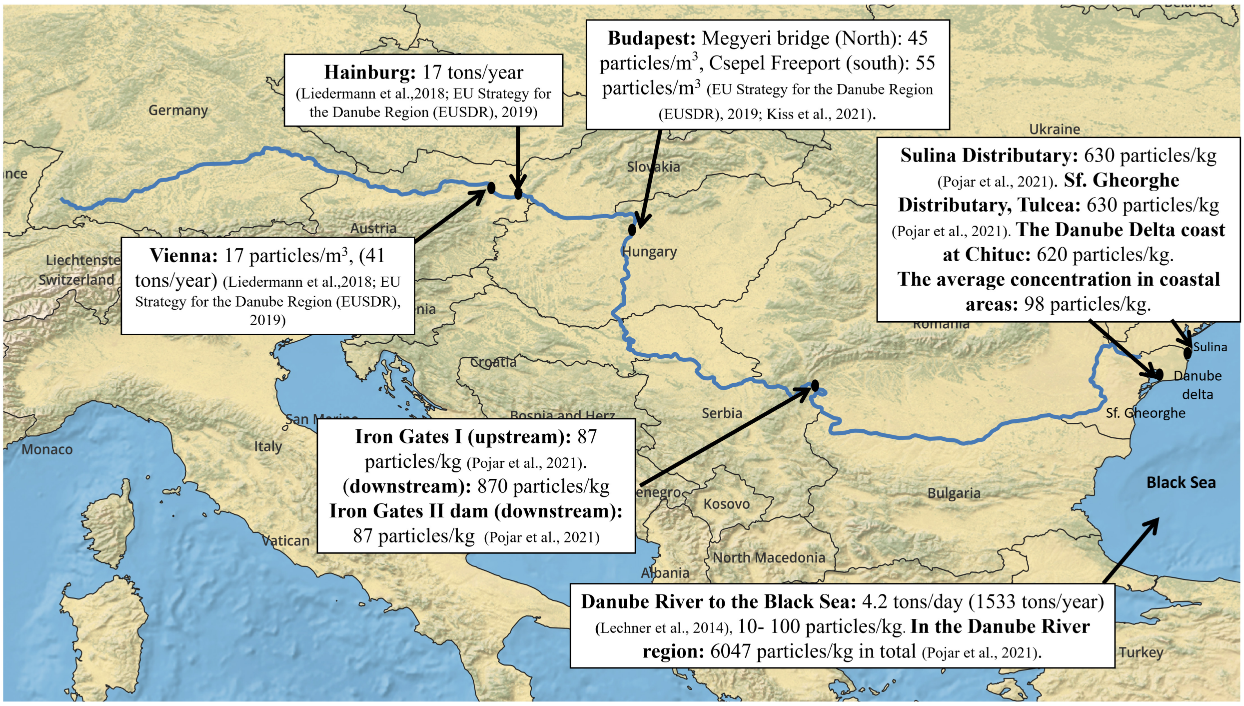

FIGURE 1
The amount of MPs in different regions of the Danube River from its source to the Black Sea, based on the various research results. Values are shown using the original units reported in each study; conversion was not performed where particle mass or size information was unavailable. Base map data were obtained from Natural Earth (www.naturalearthdata.com).

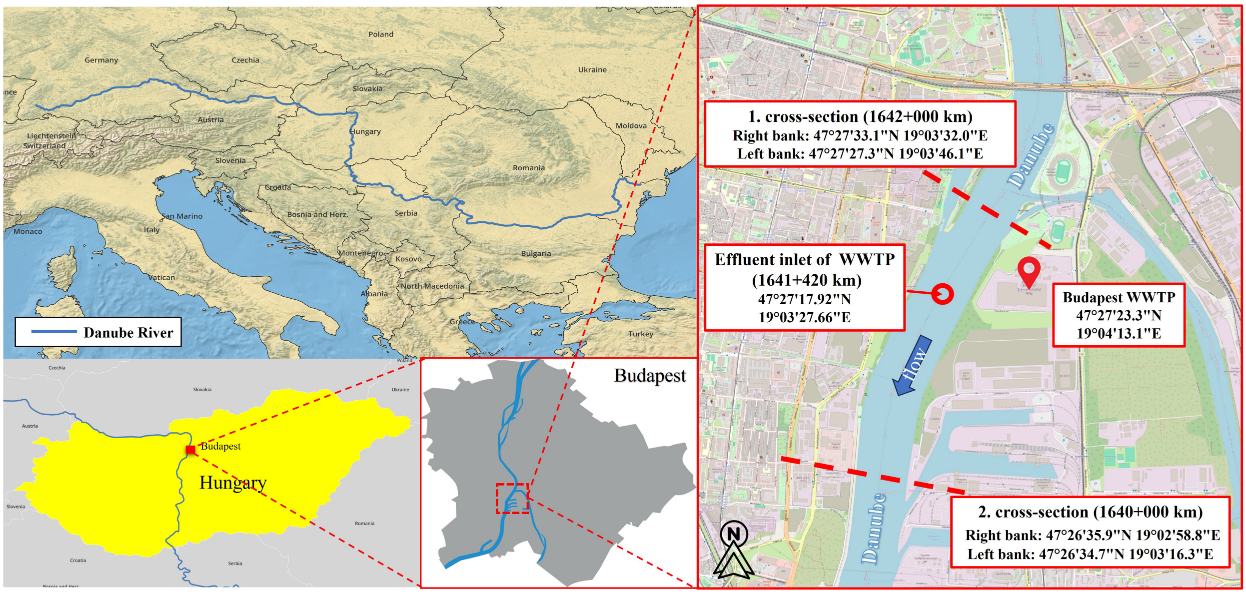

FIGURE 2
Basin-scale overview of the Danube River from the source to the Black Sea, focusing on the Hungarian section within Budapest. Sampling points are situated at the Danube River km 1,642 + 000 (Right bank: 47° 7′ 33.1″ N 19° 3′ 32.0″ E, to Left bank: 47° 7′ 27.3″ N 19° 3′ 46.1″ E) and 1,640 + 000 (Right bank: 47° 6′ 35.9″ N 19° 2′ 58.8″ E to Left bank: 47° 6′ 34.7″ N 19° 3′ 16.3″ E), (right figure). Base map data were derived from Natural Earth and OpenStreetMap (© OpenStreetMap contributors).

specifically in the urban area of Budapest. Each cross-section had 9 sampling points, arranged horizontally and vertically across the water column. This yielded a total of 18 depth- and laterally resolved observations. This approach enabled a detailed assessment of spatial heterogeneity within each cross-section while minimizing the confounding effects of temporal hydrological variability.

The MLM net was deployed from a pontoon. A crane lowered the nets to their target depths, secured with stoppers on the cable, while a tail blade kept them aligned with the flow. Each deployment

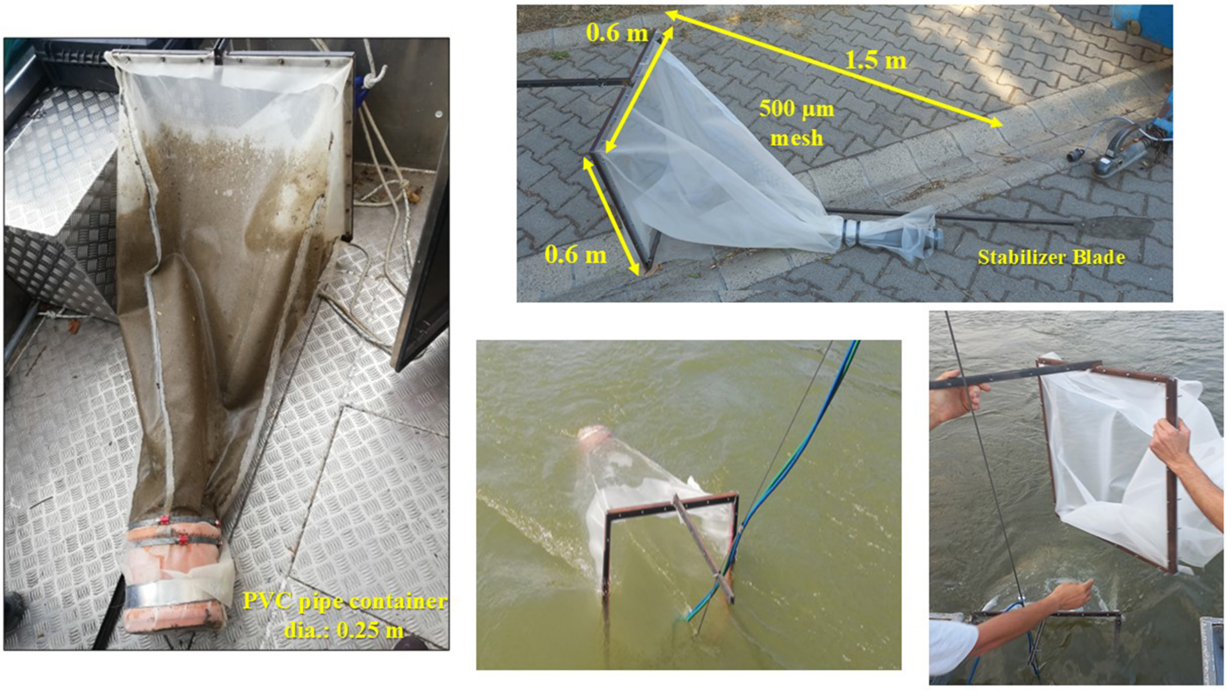

FIGURE 3
Multilevel manta net device.

lasted 30 min, after which the nets were retrieved and rinsed with pressurized water to transfer collected material into the containers.

Flow velocities across the cross-sections were measured using an Acoustic Doppler Current Profiler (ADCP). As ADCP readings are less reliable close to the riverbed, the flow profiling was supplemented by near-bed measurement by an Acoustic Doppler Velocimeter (ADV) mounted on the bed-level frame.

To assess how changes in flow discharge (Q) during flood conditions influence MP loads, two additional sampling campaigns were carried out in winter 2023 (Figure 4). A portable Manta net (0.12 m × 0.35 m frame, 0.70 m net length, 1,000 µm mesh) was fixed at a near-surface point upstream of the cross-sections (47° 8′ 50. 2" N, 19° 3′ 31. 7" E) and deployed for 1 h, twice daily, during two flood events. Q, water levels, and flow velocities were verified using data from the Budapest gauge station (1,646+500 river km) and ADCP measurements.

2.2 Laboratory analysis

After field collection, samples were transferred to sealed containers and transported to the laboratory, where they were refrigerated until analysis to minimize microbial activity. To separate plastics from sediments and organic material, samples were placed in beakers filled with a saturated sodium chloride (NaCl) solution and allowed to settle for 24 h (Masura et al., 2015; Stock et al., 2019). As most plastics are less dense than the solution, they float while heavier particles sink. Floating material, including potential MPs (even in the settled material), was gently removed using a spoon and tweezers and transferred to aluminum pans. These samples were then dried at 40 °C for 24 h before being sieved, and particles smaller than 5 mm were retained for further processing.

Remaining organic matter and microorganisms were removed by immersing the samples in 35% hydrogen peroxide (H_2O_2) for 24 h (Hidalgo-Ruz et al., 2012; Masura et al., 2015; Löder et al., 2017; Stock et al., 2019; Adomat and Grischek, 2021). Although treatment times vary with contamination levels, visual inspection confirmed that 24 hours was sufficient in this study: organic material was fully degraded, and plastic particles appeared cleaner and brighter. Longer exposure did not improve cleaning and may damage certain polymers, as noted in previous studies (Löder et al., 2017; Stock et al., 2019). After treatment, the floating material was collected again, transferred to pans, and dried for an additional 24 h at 40 °C (Masura et al., 2015). Visible plastic particles (>500 µm) were manually extracted using tweezers and stored in labeled Petri dishes for identification. To ensure accuracy, fibers and particles too small to be reliably distinguished by eye were not included at this stage.

Polymer types were identified using a Bruker Tensor 37 FTIR spectrometer with ATR mode, operating between 400 and 4,000 cm^{-1} at a resolution of 2 cm^{-1} and 16 scans. FTIR analysis determines polymer composition by comparing the absorbance spectrum of a particle with reference spectra in the instrument's library. As the library contains spectra of pristine materials, some discrepancies may arise from surface impurities. In such cases, the spectrum providing the closest match (the spectral matches exceeded 750 out of 1,000 in clarity) was used for identification, indicating a reliable correspondence between the measured spectrum and the reference database. Particle dimensions were measured using a Keyence VH-Z20UR digital microscope

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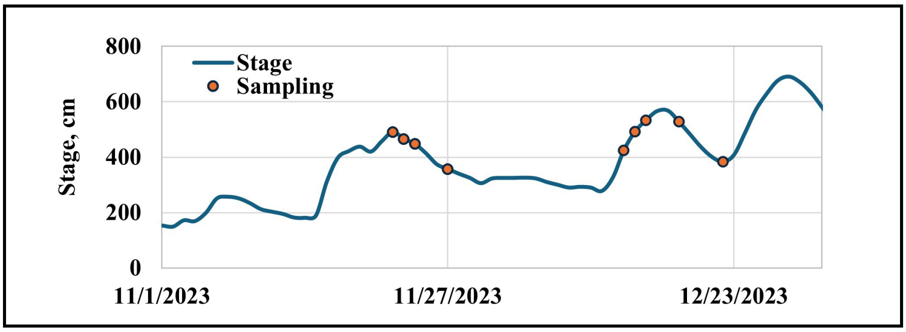

FIGURE 4
MP monitoring during two floods in november-december 2023.

(20–200×), and the total mass of extracted MPs was determined using a Shimadzu AUW120D analytical balance (precision ± 0.01 mg for 0–42 g and ± 0.1 mg for 0–120 g). All recovered particles were individually counted for each sample.

The filtered water volume (V, m^3) for each sampling event (in each point) was calculated as the product of the net's entrance area (A, m²), mean flow velocity (v, m/s), and sampling duration (t, s). C_{MP} (µg/m^3) was then determined by dividing the sample mass (m, kg) by V. The transport rate (q_{MP}, g/s) was calculated by multiplying C_{MP} by v. Transport rates were calculated independently for each cross-section and subsequently averaged to obtain a representative reach-scale estimate under the sampled hydrological conditions. Daily and annual transport values were derived as conditional extrapolations assuming temporally constant discharge and microplastic flux during the sampling period. Particle-based concentrations (particles/m^3) were calculated in parallel to allow comparison with previous studies. Our findings indicate that a mass-based approach provides a more robust estimate of MP load than particle counts alone, as it incorporates differences in particle size, density, and composition (Koelmans et al., 2020; Thornton Hampton et al., 2022; Liu et al., 2023; Xu et al., 2023; Range et al., 2025). After importing and cleaning the dataset, removing incomplete entries, and categorizing samples by depth and lateral position, C_{MP} and q_{MP} were calculated from blank- and recovery-corrected values and integrated with discharge data, following standard MP quantification procedures (Masura et al., 2015; Koelmans et al., 2019). Descriptive statistics [mean, median, range, standard deviation (SD), coefficient of variation (CV)] were computed to characterize variability within each cross-section. Because the data were non-normally distributed and sample sizes per group were small, non-parametric tests were applied throughout, in line with recommendations for environmental contaminant datasets (Helsel, 2012). Vertical and lateral differences were evaluated using the Kruskal and Wallis (1952) test, while temporal and cross-sectional differences were tested using the Mann–Whitney *U* test (Mann and Whitney, 1947). The influence of discharge on C_{MP} and q_{MP} was quantified using Spearman's rank correlation (Spearman, 1904) to capture monotonic relationships typical of riverine systems. This workflow provided a robust basis for examining the spatial structure and hydrological drivers of MP dynamics during the flood event.

3 Result

Based on the findings, the C_{MP} in the investigated section of the Danube River ranged from 0 to 0.5 mg/m^3. The first cross-section exhibited an average C_{MP} of 0.097 mg/m^3 or 54 particles/m^3, while the second cross-section showed 0.143 mg/m^3 or 75 particles/m^3. Overall, the average for both cross-sections was 65 particles/m^3. According to repeated testing conducted in the downstream cross-section in 2023, the mean C_{MP} was 0.498 mg/m^3, or 218 particles/m^3.

Consequently, in 2022, the estimated q_{MP} from these two cross-sections was 147.76 and 216.98 mg/s, respectively, using the average C_{MP} and Q = 1,500 m^3/s, as measured with the ADCP device during the test. In 2023, the estimated q_{MP} from the second cross-section was 1,058.91 mg/s under Q=2,126 m^3/s.

The mean q_{MP} in each cross-sectional area was calculated. Subsequently, the average of these two values was regarded as the overall q_{MP} per second in the study reach, and the corresponding quantities for a day and a year were subsequently derived. The daily and annual transport estimates presented here represent conditional extrapolations based on the sampled discharge conditions and should be interpreted as snapshot estimates rather than long-term averages. These findings reveal that in 2022, an estimated flow rate of approximately 0.2 g/s of MPs occurs under the investigated water flow conditions, corresponding to approximately 15.76 kg/ day and roughly 5.75 ton/ year. It is essential to note that this measurement applies specifically to MP particles ranging from 5 mm to 500 µm, as determined by the mesh size of the nets. Moreover, in 2023, the results revealed that approximately 1.06 g/s, 91.5 kg/ day, and 33.39 ton/ year of MPs passed through the second cross-section under the specified flow rate (Q, 2,126 m^3/s). The outcomes obtained from the experimental trials and subsequent computations are illustrated in the accompanying figures (Figures 5–7). The mass flow of MPs was observed throughout the entire cross-sectional area of the investigation site. The increased quantity observed over these 2 years cannot be fully explained with certainty. However, it is likely driven by several factors, such as the rising use of plastic materials in the region, ineffective waste management practices, a higher prevalence of primary MPs, and the faster degradation of macroplastics entering the aquatic environment, whether from local sources or upstream areas. Further research is needed to

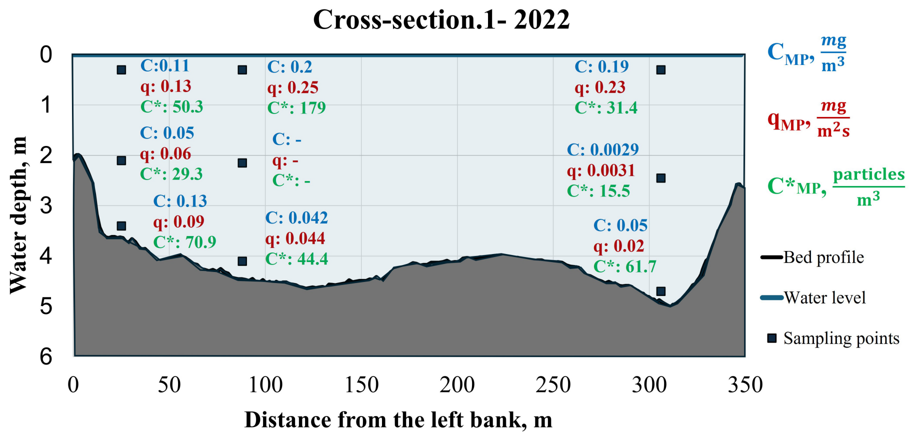

FIGURE 5
The MP delivery rate and concentration in each sampling point in cross-sections. 1 in 2022 ($Q = 1{,}500\ m^3/s$).

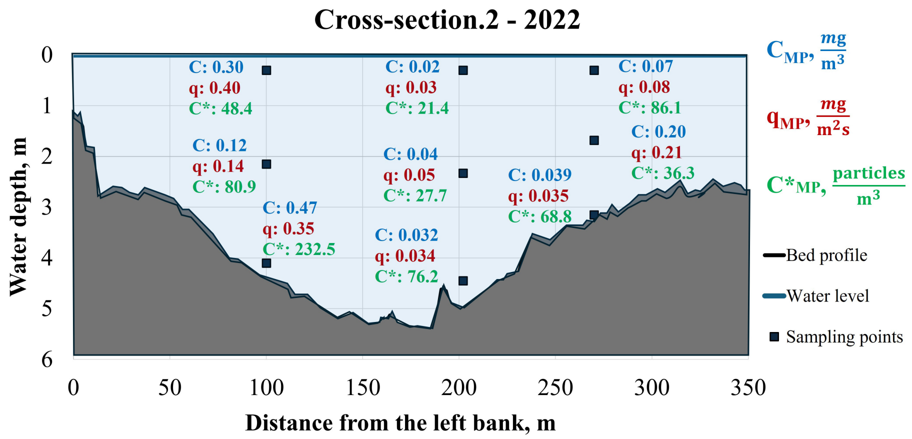

FIGURE 6
The MP delivery rate and concentration in each sampling point in cross-sections. 2 in 2022 ($Q = 1{,}500\ m^3/s$).

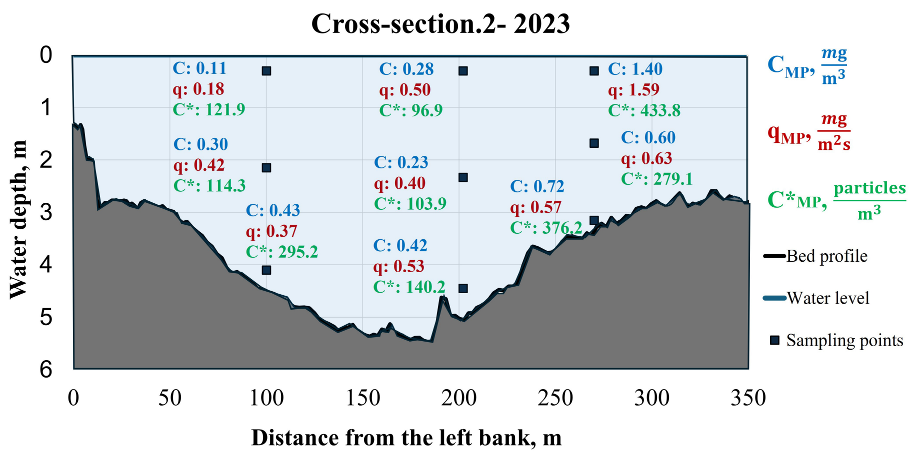

FIGURE 7
The MP delivery rate and concentration in each sampling point in the second cross-sections (downstream of WWTP) in 2023 ($Q = 2{,}126\ m^3/s$).

TABLE 1 Descriptive statistics for CMP and qMP (Flux) in each cross-section (*n*: Number of sampling points considered in the calculation; Min: Minimum; Max: Maximum; SD: Standard deviation; CV: Coefficient of Variation).

Cross-section (CS-year)	Variable	*n*	Mean	Median	Min	Max	SD	CV
CS 1-2022	Concentration	8	0.097	0.081	0.003	0.201	0.073	0.754
	Flux	8	0.104	0.076	0.003	0.25	0.093	0.896
CS 2- 2022	Concentration	9	0.143	0.068	0.018	0.468	0.154	1.081
	Flux	9	0.147	0.077	0.026	0.396	0.142	0.966
CS 2- 2023	Concentration	9	0.498	0.417	0.115	1.398	0.385	0.773
	Flux	9	0.576	0.503	0.179	1.586	0.401	0.697

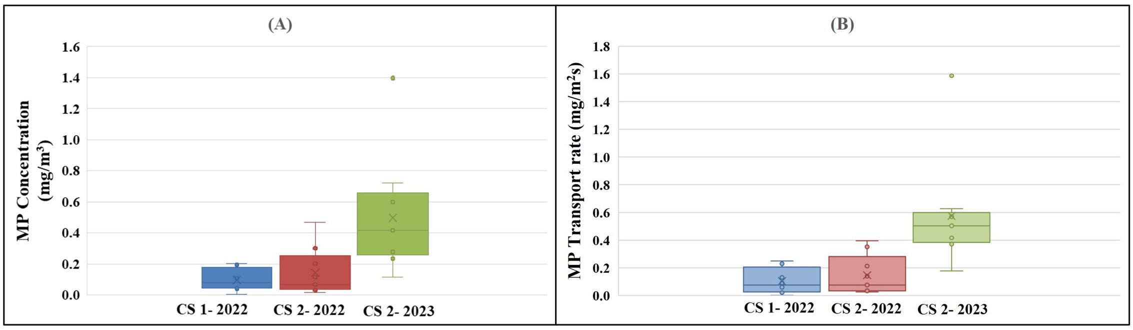

FIGURE 8
Distribution of MP mass concentration [CMP, **(A)**], and MP transport rate or flux [qMP, **(B)**] across different river cross-sections (CS), and sampling years. Boxes represent the interquartile range, the central line indicates the median, whiskers denote minimum and maximum values, and points represent individual samplings.

determine the exact underlying causes. MP concentrations were highly variable within and between cross-sections (Table 1 and Figure 8). Mean concentrations increased from 0.097 mg/m^3 and 0.143 mg/m^3 in the 2022 cross-sections to 0.498 mg/m^3 in 2023, with similarly elevated transport rates (0.104–0.147 mg/m^2·s in 2022 vs. 0.576 mg/m^2·s in 2023). Kruskal–Wallis tests showed no statistically significant vertical differences among surface, mid-depth, and near-bed samples within any cross-section (p = 0.13–0.88). Lateral variability across left-, mid-, and right-bank positions was also not statistically significant (p = 0.06–0.76), although spatial trends were observed in some cases. Mann–Whitney U-tests revealed no significant difference between the two 2022 cross-sections (p = 0.963), whereas MP concentrations in 2023 were significantly higher than in both 2022 surveys (p = 0.013–0.0006). Spearman rank correlations indicated strong positive relationships between discharge and both MP concentration (ρ = 0.66, $p <$ 0.001) and transport rate (ρ = 0.76, $p <$ 0.001). The results of the statistical analyses are presented in Table 2.

Furthermore, the FTIR analysis identified possible sources of the polymers in the collected samples, suggesting that improper recycling and storage practices may contribute to their introduction into surface water bodies. Among the various polymers identified, PS (from packaging and construction insulation; 37.97%), PE (from plastic bag and shampoo bottle production; 18.15%), and PP (commonly used in packaging and food storage containers; 10.96%) were found to be the most abundant, alongside other polymers (24.66% in total), such as Thermoplastic Vulcanizates (TPV, used in automotive components, building and construction products, household appliance parts, and electrical components; 4.20%), PA or commonly known as nylon (used in textiles, automotive industry, carpets, kitchen utensils and sportswear; 2.03%), Styrene-Ethylene-Butylene-Styrene (SEBS, used in items such as grips, handles, bumpers, and other requiring soft-touch, medical Devices; 1.03%), High-Density Polyethylene (HDPE, used in the production of plastic bottles, corrosion-resistant piping, geomembranes and plastic lumber; 0.85%), PET (used in bottle manufacturing; 0.04%), Thermoplastic elastomer/Thermal Plastic Styrene (TPE/TPS, used in toothbrushes, dashboards, and cable covers; 0.07%), PVC (used in pipe and floor covering production, and cable insulation; 0.04%), as well as non-plastic materials like organic matter and carbon. The types of MP polymers and their relative abundances (%), determined through FTIR analysis, are presented in Table 3.

Moreover, a thorough MP examination of the collected specimens was conducted to determine the size distribution of MP particles. The variety of particle sizes, shapes, and colors under investigation is illustrated in Figures 9–11. According to the analysis results, the most common MP particle shapes are fragment, linear, foam, and flake. The most observed colors among the MP particles are yellow, black, semi-yellow, grey, and green.

The stationary sampling findings in 2023 suggest the relationship between C_{MP} (mg/m^3) and Q (m^3/s), which is illustrated in Figure 12, with the best-fit curve modeled as an exponential relationship $y = 0.0008e^{0.0014x}$. The coefficient of determination (R^2 = 0.40) indicates a moderate correlation

TABLE 2 Inferential statistics (significance tests).

Kruskal–Wallis: depth differences (surface vs middle vs near-bed)			
Cross-section (CS- year)	*H* statistic	*p*-value	Interpretation
CS 1 – 2022	4.03	0.133	No statistically significant depth-related differences
CS 2 – 2022	0.27	0.875	No statistically significant depth-related differences
CS 2 – 2023	1.07	0.587	No statistically significant depth-related differences
Kruskal–Wallis: lateral differences (left vs. middle vs. right)			
Cross-section (CS- year)	*H* statistic	*p*-value	Interpretation
CS 1 – 2022	0.56	0.757	No significant lateral difference
CS 2 – 2022	5.69	0.058	Not statistically significant, though indicative of spatial variability
CS 2 – 2023	5.42	0.066	Borderline, but not significant
Mann–Whitney U: between cross-sections (concentration)			
Comparison	*U* statistic	*p*-value	Interpretation
CS 1 – 2022 vs. CS 2 – 2022	35	0.963	No significant difference between 2022 sections
CS 1 – 2022 vs. CS 2 – 2023	3	0.00058	Statistically significant increase in 2023
CS 2 – 2022 vs. CS 2 – 2023	12	0.0134	Significant increase in 2023
Spearman correlation: discharge vs concentration and flux			
Relationship	Spearman ρ	*p*-value	Interpretation
Concentration vs. discharge	0.663	0.000224	Strong, significant positive monotonic relationship
Flux vs. discharge	0.76	6.68E-06	Very strong, significant positive relationship

between Q and C_{MP}. The R^2 value suggests that the Q explains approximately 40.12% of the variability in C_{MP}. The moderate R^2 value suggests that while river discharge has a significant influence on C_{MP}, other factors, such as local hydrodynamic conditions, pollution sources, or sediment resuspension, may also contribute to the observed variability. The upward trend suggests that higher discharge rates are associated with increased MP concentrations, possibly due to enhanced transport of MPs from upstream sources or resuspension from riverbeds. However, further validation and more comprehensive datasets are needed to confirm this trend and improve the reliability of the correlation. Future experiments should include a broader range of discharged values, seasonal variations, and replicate measurements to refine the relationship and better understand the underlying mechanisms.

TABLE 3 MP polymer type and its relative abundances were determined through FTIR analysis related to the cross-sectional sampling in 2022 and 2023.

Polymer type	Amount (%)
PS	37.97
PE	18.15
PP	10.96
TPV	4.20
SEBS	1.03
PA	2.03
HDPE	0.85
TPE	0.07
PET	0.04
PVC	0.04
Other Polymers	24.66

4 Discussion

Our findings from the Hungarian section (Budapest reach) of the Danube reveal clear spatial and temporal variability in C_{MP}, consistent with the complex hydrodynamic and anthropogenic influences known to shape MP dynamics in this river system. The reported daily and annual MP transport rates were obtained through conditional extrapolation of measured cross-sectional fluxes and therefore represent snapshot estimates constrained by the sampled discharge conditions rather than long-term averages. In 2022, concentrations ranged from 54 particles/m^3 upstream to 75 particles/m^3 downstream. In 2023, downstream values rose sharply to 218 particles/m^3. As shown in Figure 1, this pattern aligns with previously reported increases along the longitudinal profile of the Danube (Lechner et al., 2014; Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019; Bermúdez et al., 2021; Pojar et al., 2021), underscoring the combined influence of local urban sources and basin-scale hydrology.

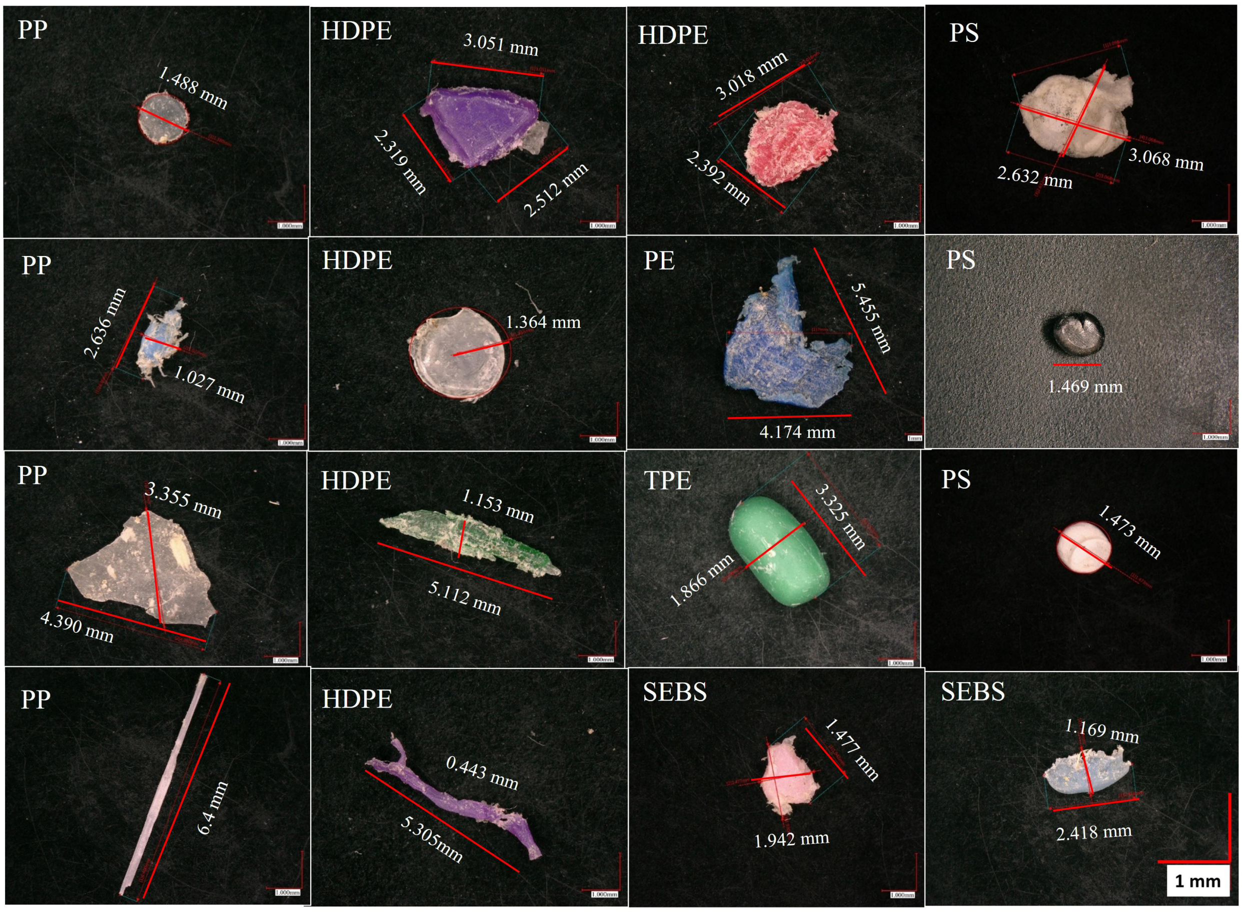

FIGURE 9
MP particles with different sizes, colors, and polymer types under a digital microscope.

Additionally, the stationary sampling findings, combined with the portable Manta net, suggest that discharge and velocity generally increase, promoting the transport of MP, while the flow regime influences MP sedimentation (Lu et al., 2023; Akdogan and Guven, 2024). It is assumed that MPs tend to settle or accumulate in areas with slower currents during periods of lower flow (Xia et al., 2021). Conversely, flood events resuspend these particles (Balla et al., 2024). Perennial low-flow conditions show minor fluctuations in C_{MP} (Drummond et al., 2022). Post-flood, MPs accumulate in slow-flow regions, and downstream, macroplastic transport lessens, potentially reducing new MP input (Drummond et al., 2022). However, as macroplastics degrade, they contribute to localized MP levels. Increased discharge during floods mobilizes residual particles from prior floods and degraded fragments, raising C_{MP} in subsequent flood events (Xia et al., 2021; Akdogan and Guven, 2024). The substantial increase in 2023 coincided with a flood event, and both C_{MP} and q_{MP} were strongly correlated with discharge, confirming that high-flow conditions act as a dominant driver of MP mobilization and export in this reach.

The sampling strategy was designed to investigate the vertical and lateral distribution of MPs within river cross-sections rather than to conduct continuous or longitudinal monitoring. To minimize the influence of short-term hydrological variability, all cross-sectional sampling was performed within a single day under near-constant discharge conditions. Due to logistical constraints associated with multilevel net deployment and the need to maintain stable hydrodynamic conditions, sampling was limited to two representative cross-sections within an urban reach of the Hungarian Danube in Budapest. Each cross-section was sampled at nine discrete points distributed laterally and

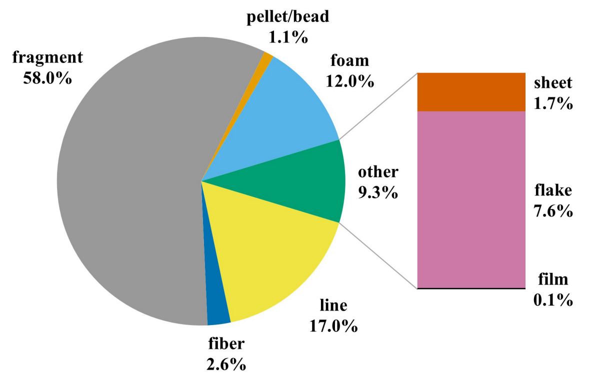

FIGURE 10
Prevailing MP shapes in the collected samples.

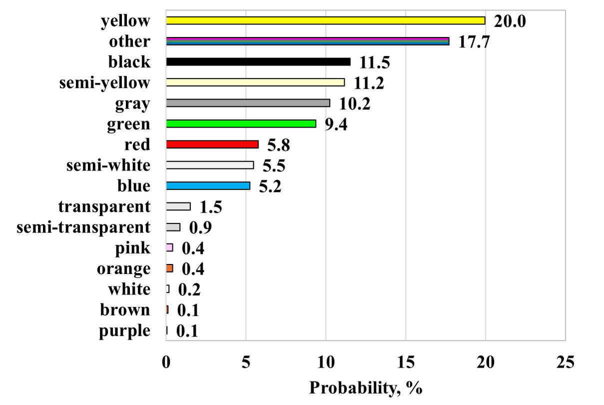

FIGURE 11
Occurrence of different colored MPs in the collected samples.

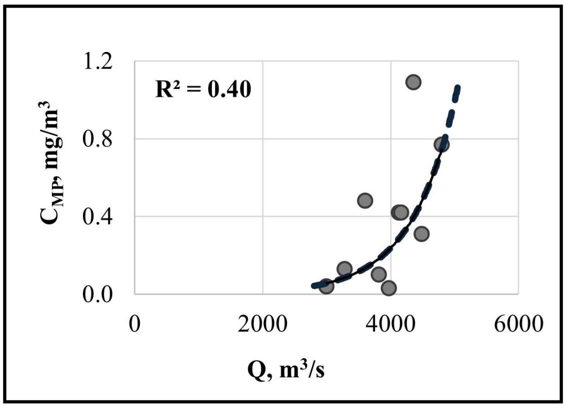

FIGURE 12
Correlation curve based on the mean daily CMP and *Q* values.

vertically across the water column, enabling high-resolution characterization of cross-sectional heterogeneity under comparable flow conditions. This design ensured internal consistency and robust interpretation of spatial patterns within the water column. The results demonstrate that MPs are not confined to surface waters but are distributed throughout the river depth, highlighting the importance of depth-resolved sampling in large, high-energy river systems. Future studies should extend this framework to additional cross-sections and flow regimes to capture broader longitudinal and seasonal variability. MPs were detected across all sampled vertical and lateral positions within the investigated cross-sections, indicating their widespread presence throughout the water column. However, their spatial distribution exhibited notable variability, reflecting complex, particle-specific transport mechanisms rather than uniform behavior. The observed patterns likely result from the combined influence of turbulent dispersion and stochastic particle motion under the prevailing hydraulic conditions. Accordingly, the absence of statistically significant mass-based vertical or lateral differences should not be interpreted as evidence of complete mixing. Localized enrichment of MPs near the riverbed further suggests that settling and temporary retention may occur under certain flow regimes, depending on particle properties and local hydrodynamics. These findings suggest a dynamic balance between suspension, transport, and short-term deposition, underscoring the need for future studies to integrate bed-sediment analyses with water-column measurements to better understand the storage and resuspension processes of MPs. The large cross-sectional area of the Danube at Budapest, combined with high turbulence and shear stress, likely promotes rapid homogenization of buoyant (PP, PE) and slightly negatively buoyant particles. However, the tendency for elevated concentrations along the right bank in both 2022 and 2023 indicates localized source influences and the possible role of secondary circulation cells, which may focus floating debris on one side of the channel patterns, also noted in other large rivers. Although these differences were not statistically significant, they suggest hydrodynamic controls that warrant further investigation.

The observed increase in MP concentrations between sampling years and the strong temporal contrasts between 2022 and 2023 demonstrate that hydrological events are critical periods of MP export. Under higher discharge (−2126 m^3/s), increased shear stress, bank erosion, and scouring of near-bank deposits likely release previously stored plastics, while enhanced turbulence promotes resuspension of bed-associated MPs. These observations align with prior studies emphasizing the role of floods and storms in releasing MPs from floodplains and retention zones (Habersack et al., 2016; Pojar et al., 2021). Our results, therefore, support the interpretation that flood-driven conditions represent disproportionately important windows for MP transport and that routine monitoring focused only on baseflow conditions would likely underestimate annual loads. Furthermore, even the regulatory efforts to reduce plastic pollution may not immediately translate into lower riverine loads due to environmental lag times, legacy plastics stored in urban catchments, and episodic local inputs. Depth-resolved data from this study also indicate that settling and transient storage may occur under certain conditions, further contributing to temporal variability in measured concentrations. These findings underscore the importance of discharge and timing when interpreting MP trends across years.

The polymer composition in our samples was dominated by PE, PP, and PS, consistent with global trends and earlier work along the Danube (Lechner et al., 2014; Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019; Bermúdez et al., 2021; Pojar et al., 2021). Shape and color analysis provide additional information on MP sources and environmental processing. The predominance of fragments suggests ongoing breakdown of larger macroplastic debris, whereas the limited presence of fibers likely reflects methodological constraints- specifically, the use of a 500 μm net and visual sorting, which are known to underestimate thin or transparent fibers. Color distributions also help identify potential origins (e.g., consumer packaging vs. industrial pellets) and indicate whether particles have undergone weathering or discoloration. Although our dataset suggests a dominance of degraded secondary MPs, integrating automated spectroscopic analysis in future work would allow more robust identification of source pathways.

Our values are broadly comparable to those obtained by the Tiny Plastic Puzzle project in Budapest (Gaál, 2018; Interreg Danube Transnational Programme, 2019; Kiss et al., 2021), which reported 45–55 particles/m^3 at Megyeri Bridge and Csepel

Freeport (corresponding to the river reach investigated in our study), consistent with our 2022 measurements. At the basin scale, Figure 1 illustrates how our values align with the broader Danube profile, which exhibits increasing concentrations and fluxes from upstream regions toward the middle and lower reaches (Lechner et al., 2014; Liedermann et al., 2018; Interreg Danube Transnational Programme, 2019; Bermúdez et al., 2021; Pojar et al., 2021). Downstream in Romania and the delta, sedimentary MPs dominate, with concentrations exceeding 6,000 particles/kg (Habersack et al., 2016; Pojar et al., 2021), suggesting that MPs not captured in the water column in Hungary may be progressively stored in depositional zones. Given that sediment flux along the Danube has declined by −60% due to damming and hydromorphological regulation (Habersack et al., 2016; Pojar et al., 2021). Retention of MPs in impoundments and floodplains is likely substantial. Because our study focused exclusively on the water column, future work should incorporate both sediment and floodplain sampling to quantify long-term storage and remobilization processes. The MP fluxes estimated in this study are lower than those reported by Liedermann et al. (2018) and the Interreg Danube Transnational Programme (2019), despite our sampling sites being located downstream of their study reaches (Figure 1). This difference is most likely due to differences in hydrological conditions, temporal coverage, and study objectives rather than methodological inconsistencies. While previous studies reported annual or long-term integrated loads that include high-flow and flood events, our measurements represent short-term, flow-specific conditions under near-steady discharge. High-discharge events are known to strongly enhance MP mobilization and downstream transport. Temporal differences between the studies may also contribute to the observed variability. Changes in waste management practices, wastewater treatment efficiency, and plastic consumption patterns within the Danube basin over recent years may have altered MP emissions. In addition, depth-resolved observations in our study indicate that MPs may be temporarily retained near the riverbed during lower-flow conditions, reducing instantaneous water-column fluxes. Therefore, our results should be interpreted as conservative, event-scale estimates that complement, rather than contradict, basin-scale flux assessments reported in earlier studies.

The comparison between our fragment-dominated assemblages and the fiber-rich deposits reported downstream (Lechner et al., 2014; Habersack et al., 2016; Interreg Danube Transnational Programme, 2019) highlights a methodological gap that should be addressed in future monitoring programs. Smaller, more flexible fibers can bypass net-based samplers yet accumulate in depositional environments, highlighting the need for integrated strategies that employ multilevel manta nets, pump filtration with finer mesh sizes, and sediment sampling. Equally important is harmonizing units across studies (e.g., particles/m^3 vs. mg/m^3 vs. particles/kg), which currently limits cross-study comparability along the Danube and globally. Using both concentration and transport rate metrics, as done here, provides a more complete understanding of MP dynamics by distinguishing between particle abundance and discharge-driven export capacity. Direct conversion of MP concentrations reported in the literature was not possible for most studies, as summarized in Figure 1, as essential information on particle size distribution, mass, and polymer density was not provided. Without these parameters, conversion between particle-based and mass-based units would require assumptions that could substantially bias estimates of MP abundance. Consequently, values were compared using their original units, and this methodological limitation is acknowledged when interpreting inter-study differences.

This study has several limitations that should be considered when interpreting the results. First, sampling was restricted to two cross-sections within the urban reach of the Danube and conducted under limited hydrological conditions; therefore, the findings should not be extrapolated to the entire river or to different flow regimes. Second, the MLM net employed a mesh size of 500 µm, which excludes smaller MPs and fibers, so the reported concentrations and fluxes represent only the coarse MP fraction (500 µm−5 mm). Third, water-column sampling does not fully capture processes related to MP deposition, storage, and resuspension in bed sediments, which may be important under certain hydraulic conditions. Finally, daily and annual transport estimates are conditional extrapolations based on snapshot measurements and should be interpreted as indicative rather than long-term averages. Despite these limitations, the study provides robust cross-sectional insights into the vertical and lateral distribution of coarse MPs in a large river system.

Despite these limitations, our approach provides several novel contributions compared to earlier studies along the Danube. The use of a customized MLM net system allowed us to resolve vertical and lateral variability that would be missed by surface-only sampling, while the simultaneous calculation of C_{MP} and flux under changing hydrological conditions offers new insights into event-driven MP transport. Moreover, our high-resolution temporal design, which samples before, during, and after a flood, captures dynamic behavior that single-timepoint surveys cannot resolve. Future campaigns should include targeted sampling during storm events to evaluate the potential contribution of WWTPs during overflow or bypass conditions, which may represent an episodic but significant source of MP.

Overall, our results underscore the necessity for spatially and temporally detailed monitoring strategies, standardized methods, and basin-wide coordination to accurately quantify MP transport along the Danube River. The combined influence of urban inputs, hydrological variability, and river regulation underscores the complexity of MP dynamics in large rivers and the importance of integrating hydrological events into monitoring and management frameworks.

5 Conclusion

This study provides a multilevel Manta (MLM) net-based, depth- and laterally resolved assessment of microplastic concentrations and transport rates for the coarse size fraction (500 µm−5 mm) within the Budapest reach of the Danube River. By integrating field sampling, laboratory preparation, and FTIR-based polymer identification, we quantified C_{MP} and MP fluxes under contrasting hydrological conditions. In 2022, the mean C_{MP} was 0.120 mg/m^3 (65 particles/m^3), corresponding to an estimated flux of 0.2 g/s (≈15.8 kg/ day; 5.75 ton/ year). In 2023, during a high-discharge period, C_{MP} increased to 0.498 mg/m^3 (218 particles/m^3), resulting in substantially higher fluxes of 1.06 g/

s (≈91.5 kg/ day; 33.4 ton/ year). These findings demonstrate the strong influence of hydrology on MP exports, with flood-driven conditions acting as critical periods of enhanced mobilization and downstream transport.

The polymer composition was dominated by PS (37.97%), PE (18.15%), and PP (10.96%), reflecting potential links to consumer and packaging-related sources. The particle shapes and colors indicated the prevalence of secondary fragments and weathered debris. Although the MLM net enabled multilevel characterization, the use of a 500 µm mesh inevitably led to an underestimation of microfibers and smaller particles, suggesting that our flux estimates are conservative. Additional uncertainties arise from flow variability, limitations in visual sorting, and the exclusion of sediments, where substantial MP storage is known to occur.

Overall, this study highlights the importance of harmonized spatial and temporal monitoring strategies across the Danube River Basin, particularly during storm and flood events when MP loads are at their highest. Future work should integrate finer-mesh or pump-based sampling, sediment and floodplain surveys, and targeted assessments of potential point sources such as wastewater treatment plant discharges during overflow conditions. These coordinated approaches will be essential for improving MP load estimates and informing basin-wide mitigation efforts aimed at reducing plastic pollution in one of Europe's major river systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. FP: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. AE: Methodology, Writing – review & editing. AS: Data curation, Writing – review & editing. DG: Data curation, Writing – review & editing. AT: Data curation, Writing – review & editing. SB: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. ChatGPT and Grammarly were employed exclusively for language editing (grammar, structure, and paraphrasing). All analytical decisions, interpretations, and scientific content remain the sole responsibility of the author(s).

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