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Spatiotemporal Patterns of Microplastic Pollution in a Freshwater Reservoir: Polymer and Morphological Evidence from Borçka Reservoir (Türkiye)

Koray Özşeker · Bilal Onmaz

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Abstract This study investigates the spatial and seasonal distribution of microplastics in Borçka Reservoir, located in the Eastern Black Sea Basin (Türkiye), based on field sampling conducted during winter 2023 and spring, summer, and autumn 2024. The samples (water–sediment) were collected seasonally from multiple stations and analyzed for microplastic abundance, morphology, size, color, and polymeric characteristics. Microplastic abundance in surface waters ranged from 0.14 to 0.31 items L^{-1}, with the highest concentrations observed in autumn 2024, while sediment concentrations varied between 8 and 32 items kg^{-1} dry weight, exhibiting relatively limited seasonal variability. Fragments (38.1%) and fibers (35.1%) dominated the microplastic assemblage, indicating that secondary microplastics derived from the fragmentation of larger plastic debris represent the main contamination source. Most particles were within the 1–2 mm size range (300–3310 µm), and transparent (21.4%) and blue (20.8%) particles were the most common color categories. Polymer analysis revealed the predominance of PETG (20.8%), PP (11.3%), PA (10.1%), ABS (10.1%), and PE (9.5%), reflecting continuous land-based inputs related to packaging materials, textile fibers, fishing activities, and industrial sources within the catchment. Overall, the results indicate that Borçka Reservoir acts as an effective sink for microplastics and highlight the need for seasonally resolved monitoring and targeted management strategies to reduce land-based microplastic inputs in freshwater reservoirs, providing transferable insights for microplastic management in dam-regulated freshwater systems.

Keywords Polymer composition · Microplastic morphology · Reservoir sediments · Anthropogenic sources · Pollution

1 Introduction

Microplastics (MPs), typically defined as synthetic polymer particles ranging from approximately 1 µm to 5 mm in size, have emerged as pervasive pollutants within aquatic environments worldwide and are now regarded as an emerging contaminant class of global concern (Korkmaz et al., 2026; Terzi et al., 2025). Their environmental persistence results from their physicochemical stability, hydrophobic nature, and resistance to microbial degradation (Baycan

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K. Özşeker (✉)
Institute of Marine Sciences and Technology, Karadeniz Technical University, Trabzon, Türkiye
e-mail: koray_ozseker@ktu.edu.tr

B. Onmaz
Department of Fisheries Technology Engineering, Faculty of Marine Sciences, Karadeniz Technical University, Trabzon, Türkiye

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et al., 2025; Ganguly et al., 2026). MPs are broadly categorized into primary microplastics, which are intentionally produced for industrial and commercial applications (e.g., microbeads in personal care products, industrial resin pellets, textile-derived synthetic fibers), and secondary microplastics, which originate from the fragmentation of larger plastic debris through environmental weathering, photooxidation, mechanical abrasion, and hydrolytic processes (Ganguly et al., 2026; Jaikumar et al., 2025; Sarkar et al., 2023). Once formed, MPs can be transported through fluvial systems, retained within water columns, and deposited into sediments, thereby establishing long-term pollution reservoirs (Aydın et al., 2023; Bazarsadueva et al., 2026).

Freshwater systems serve as critical conduits connecting terrestrial plastic waste to marine environments, and the increasing volume of plastic discharge has intensified scientific attention toward these landscapes (Jaikumar et al., 2025; Özşeker et al., (2022). Anthropogenic contributors of MPs to freshwater reservoirs include municipal wastewater effluents, industrial discharge containing synthetic polymer residuals, untreated or poorly managed sewage, surface runoff from urbanized catchments, tire wear particles and roadway dust, agricultural drainage containing plastic mulch fragments, and aquaculture-related litter such as synthetic nets and ropes (Chen et al., 2024, Mutlu et al., 2024, Wu et al., 2024, Hassan et al., 2026). Moreover, the ability of MPs to act as both chemical carriers, transporting additives such as phthalates, bisphenol A, or brominated flame retardants, and adsorption substrates for toxic metals and persistent organic pollutants (POPs) underscores their role as vectors of contaminant transfer (Amenouche et al., 2026; Cai et al., 2022; Tavşanoğlu et al., 2024). Consequently, MPs pose risks to aquatic organisms via ingestion, trophic transfer, endocrine disruption, oxidative stress, and physiological impairment, ultimately contributing to ecosystem imbalance and potential human health risks through fisheries and potable water pathways (Aydın et al., 2023; Resmi & Vaishnavi, 2025; Sharma et al., 2024a, 2024b; Solayman et al., 2026).

Although microplastic research in Türkiye has expanded over the last decade, the majority of studies are concentrated in marine and coastal ecosystems, with comparatively fewer investigations focused on inland freshwater reservoirs, which represent strategically important interfaces between riverine inputs and downstream marine systems (Gündoğdu et al., 2023; Güngör et al., 2025; Korkmaz et al., 2026; Terzi et al., 2025; Zeybek Yünlü et al., 2025). This gap limits the interpretation of microplastic transport, accumulation dynamics, and source attribution within watershed-scale pollution pathways (Mutlu et al., 2024, Şimşek, 2025, Luz et al., 2026). Borçka Reservoir, located in the Eastern Black Sea Basin, exemplifies a reservoir subjected to multiple and overlapping anthropogenic pressures (Özşeker et al., 2026a, 2026b; Şirin, 2019). Constructed primarily for hydroelectric power generation, the reservoir receives inflow from the Çoruh River and its tributaries, which drain an extensive catchment influenced by urban development, domestic sewage discharge, industrial activities including mining, fishery operations utilizing synthetic gear, agricultural production, and expanding tourism infrastructure (Özşeker et al., 2026a, 2026b).

Potential MPs inputs to Borçka Reservoir arise from point and non-point sources such as fishing ports and gear residue, litter deposition from boat traffic, improperly managed recreational waste, tourism-driven shoreline in waste management systems and insufficient treatment of domestic effluents may further exacerbate MPs accumulation (Dar & Gani, 2025; Gedik & Atasaral, 2022; Zhao et al., 2026a, 2026b). These pressures collectively indicate that Borçka Reservoir likely functions as both a sink, retaining microplastics within sediments and water columns, and a secondary source, reintroducing particles into downstream systems through hydrodynamic resuspension and outflow processes (Bazarsadueva et al., 2026).

Despite the ecological and socio-economic importance of this reservoir, there remains a notable absence of comprehensive microplastic datasets describing spatiotemporal patterns, morphological variability, polymer composition, size-dependent behavior, and potential source pathways (Tavşanoğlu et al., 2024; Zhou et al., 2025). Limited information on these parameters restricts the development of sustainable management strategies, targeted pollution mitigation, and basin-scale conservation frameworks. As such, addressing these gaps is essential to enhance scientific understanding, inform policymakers, and strengthen region-specific environmental directives (Ahmed et al., 2024; Dong et al., 2025).

Accordingly, this study hypothesizes that microplastic pollution in Borçka Reservoir exhibits measurable spatial and seasonal variability driven by heterogeneous anthropogenic pressures, hydrological processes, and fluctuations in human activity across stations. To test this hypothesis, the present investigation integrates quantitative microplastic analysis with polymer-specific identification and morphological classification techniques. The objectives of this study are to: (I) determine the abundance, spatial distribution, and seasonal variation of MPs across six sampling stations within Borçka Reservoir; (II) characterize MPs based on size, color, shape, and polymer composition to identify potential pollution sources and environmental pathways; (III) evaluate the influence of human activities, such as fishing, tourism, domestic wastewater, and industrial operations, on MPs distribution patterns; and (IV) contextualize the role of Borçka Reservoir as a potential microplastic sink within the Eastern Black Sea Basin, contributing to a broader understanding of watershed-scale pollution dynamics.

By integrating spatiotemporal datasets with detailed polymer and morphological analyses, this study strengthens the current body of knowledge on microplastic contamination in freshwater reservoirs. Moreover, the outcomes provide a scientific baseline for monitoring frameworks, support ecological risk assessment processes, and offer data-driven insights for regional management and policy implementation.

2 Materials and Methods

2.1 Description of the Study Area

This study was carried out in Borçka Reservoir, located within the administrative boundaries of Borçka district in Artvin province, northeastern Türkiye, and constructed on the Çoruh River (Fig. 1).

Within the scope of this research, sediment and water samples were collected from six stations representing distinct hydrological conditions and environmental pressures across the reservoir. To capture the longitudinal hydrological gradient and environmental variability, stations were strategically positioned at inlet and outlet zones, as well as proximal and distal sectors relative to the dam body. This spatial arrangement was designed to evaluate the influence of flow dynamics and surrounding land-use patterns on the distribution of microplastics in water and sediments (Supplementary Table 1).

Borçka Reservoir is an artificial freshwater system formed after the completion of the Borçka Dam in 2007 along the Çoruh River (Akpınar et al., 2024; Özşeker et al., 2026a, 2026b). The reservoir is located approximately 2 km southeast of the Borçka district center and extends nearly 20 km through the Çoruh Valley, with an additional 3.5 km secondary branch influenced by the Murgul Stream (Özşeker et al., 2026a, 2026b; Şirin, 2019). Periodic water level fluctuations occur due to hydropower production schedules combined with seasonal hydrological variability, which jointly regulate the reservoir's hydro-morphological structure (Yıldırımer & Özalp, 2024). Covering an area of about 10.8 km^2, the reservoir has an average depth of 45 m, a maximum depth of 96 m, and lies at an elevation of nearly 410 m above sea level (Ozseker & Eruz, 2017). The northeastern upper section is dominated by steep forested slopes with limited anthropogenic impact, whereas the southwestern section is characterized by intensified human activity, including settlements, agricultural areas, tea plantations, and active shoreline utilization. The strong flow regime and high sediment load transported by the Çoruh River play a key role in sedimentation processes and contribute to variations in depositional environments throughout the reservoir (Emïnağaoğlu et al., 2016; Özşeker et al., 2022).

Originally constructed for hydropower generation, Borçka Reservoir additionally supports irrigation, flood regulation, and intensive cage aquaculture, accounting for nearly 4% of Türkiye's inland aquaculture production (Serifoglu Yilmaz, 2025). The geological structure of the basin consists of volcanic and sedimentary formations, primarily andesite, basalt, sandstone, and shale, accompanied by mineralized zones linked to long-term mining activities in the Murgul sub-basin (Yıldırımer & Özalp, 2024). Despite its artificial origin, the reservoir exhibits notable ecological value through diverse fish assemblages (e.g., carp, trout), recreational uses, and ecotourism opportunities, thereby serving as a regionally significant freshwater resource (Özşeker et al., 2022; Turgut et al., 2015).

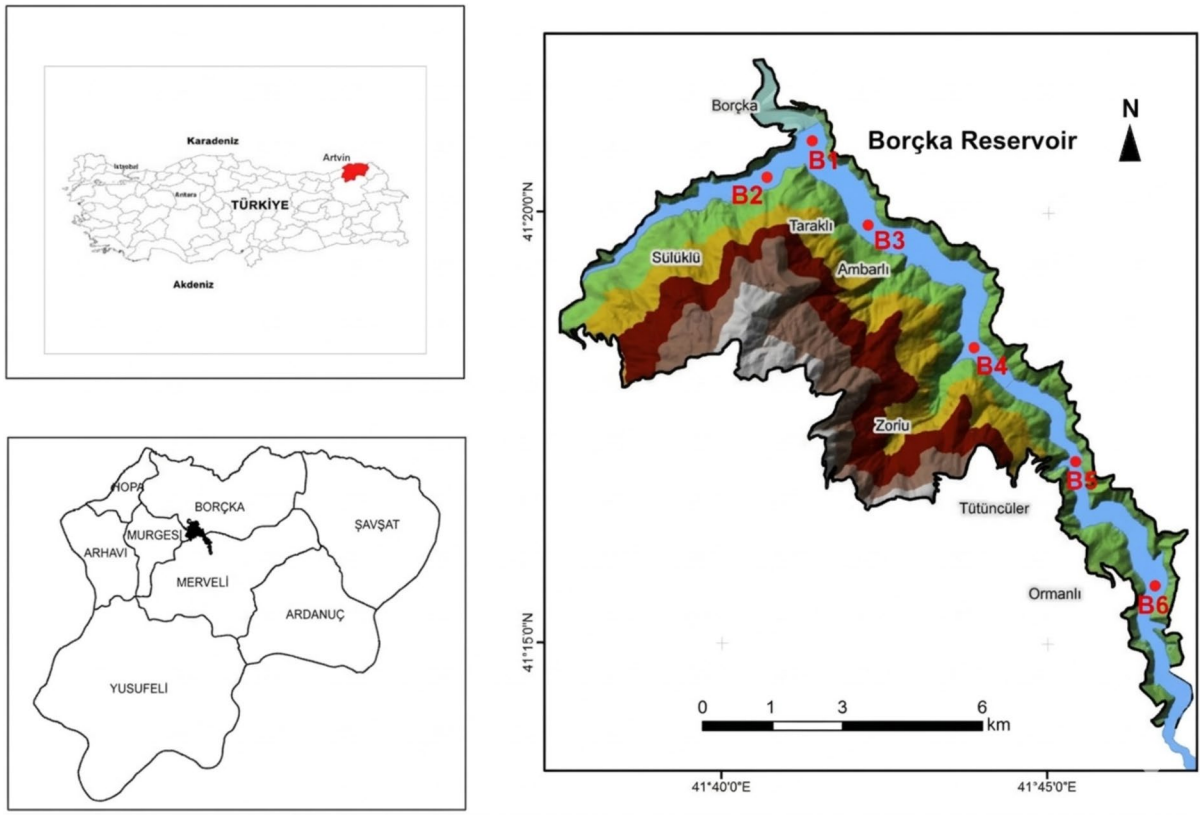


Fig. 1 Overview of Borçka Reservoir showing its regional location in Çoruh River Basin, along with the spatial distribution of sampling stations from upstream to downstream sections

2.2 Sample Collection, Processing, and Analysis

The sampling process covered four seasons, including winter 2023 and spring, summer, and autumn 2024. During each season, sediment and water column samples were collected from six stations (Fig. 1) to evaluate seasonal variation. MPs were identified and characterized based on size, color, type, and polymer composition (Manon et al., 2026; Sarkar et al., 2023; Zhou et al., 2025). This seasonal dataset provides an overview of current MPs pollution in Borçka Reservoir and supports the assessment of potential ecological risks within the aquatic ecosystem. Water column samples were collected from the surface layer at each sampling station in triplicate. During sampling, 15 L of water was obtained and transferred into 3 L glass containers using a sieving–filtration method to minimize contamination and ensure effective particle retention. In the sieving–filtration procedure, collected water samples were first passed through a stainless-steel sieve (mesh size: 5 mm) to remove large debris prior to filtration and ensure that retained particles fall within the defined MPs sizes range (<5 mm). Subsequently, the filtered water was vacuum filtered through pre-cleaned glass fiber filters to collect microplastic particles. This combined sieving and filtration approach was used to concentrate suspended particles and facilitate the subsequent microscopic identification of MPs. Sediment samples from the benthic zone were collected using an Ekman grab sediment sampler at depths of 0–2 m. The collected surface sediments were subsequently transferred into 300 mL pre-cleaned glass jars, which were filled without leaving headspace to prevent sample alteration during transport and storage. This approach allows homogeneous collection of surface sediments and improves the accuracy of microplastic assessment. All collected water and sediment samples were transported to the laboratory under controlled conditions for subsequent analyses of MPs abundance,

morphology, size distribution, and polymer composition (Song et al., 2025).

Water and sediment samples were subjected to microplastic extraction following standardized laboratory procedures. Water samples were vacuum filtered through pre-cleaned glass fiber filters, which were rinsed three times with ultrapure water and dried under clean laboratory conditions prior to use to minimize potential contamination. Sediment samples were first dried at room temperature and homogenized prior to density separation. An additional chemical digestion step was not applied prior to density separation because the sediment samples contained relatively low organic matter, and potential organic debris was excluded during microscopic examination of the particles. Given the high inorganic sediment input and non-algal turbidity characteristics of Borçka Reservoir, organic matter content in the sediment was observed to be relatively low during sample processing. Therefore, no chemical digestion step was applied to avoid potential alteration or loss of microplastic particles. Microplastics were extracted using a saturated NaCl saline solution (density ≈1.2 g cm^{-3}). Approximately 50 g of dried sediment was mixed with 200 mL of saline solution (1:4 w/v ratio) in a glass beaker and stirred thoroughly to facilitate particle suspension. The mixture was allowed to settle for 24 h to enable the separation of mineral particles and floating microplastics. The supernatant containing floating particles was carefully decanted and vacuum-filtered through glass fiber filters (pore size 1.2 µm). The filtration step allowed the collection of microplastic particles for subsequent microscopic examination. (Constant et al., 2021; Han et al., 2019; Queiroz et al., 2025). MPs were analyzed using a stereo microscope (SZX16, Olympus Co., Tokyo, Japan) positioned within an enclosed cabinet to minimize contamination. The size, shape (categorized as fiber/filament or fragment), and color of the MPs were determined, and size measurements were performed using a Touptek XCAM1080PHD camera attached to the microscope (Akdemir et al., 2025; Gündoğdu et al., 2023; Leistenschneider et al., 2024). The classification of MPs color and morphology followed the methodology described by Koelmans et al. (2019). Following the initial characterization, a randomly selected subset of MPs particles was subjected to Fourier Transform Infrared (FTIR) spectroscopy for polymer identification (Shune Thar et al., 2025; Villegas-Camacho et al., 2025). To ensure representative polymer identification, a subsampling strategy was applied for FTIR analysis. From the total pool of visually identified microplastic particles (n = 168), a randomly selected subset of 60 particles (35.7%) was analyzed using ATR-FTIR spectroscopy. The selected particles represented different morphological categories (fragments, fibers, and films), colors, and size classes to ensure that the analyzed subset adequately reflects the overall microplastic assemblage. Due to the limitations of ATR-FTIR for very small particles, polymer identification was mainly performed for particles larger than approximately 500 µm, while smaller particles were classified based on morphological observations under stereomicroscopy. This proportion of analyzed particles is consistent with methodological practices reported in previous MPs studies. The analyses were performed using an FTIR spectrometer equipped with an Attenuated Total Reflectance (ATR) unit, allowing direct measurement of particles without additional chemical preparation (Liu et al., 2024). Spectral data were acquired within the mid-infrared range of 4000–650 cm^{-1}, with a resolution of 4 cm^{-1} and 32 scans per sample to optimize signal-to-noise ratio (Liu et al., 2024; Villegas-Camacho et al., 2025). Polymer identification was achieved by comparing the obtained spectra with reference spectra from a certified polymer library, and diagnostic absorption bands were evaluated to classify polymers such as PE, PP, PS, PET, and PVC. A minimum spectral similarity threshold of ≥ 70% was adopted for polymer confirmation, consistent with criteria recommended in previous MPs studies (Serranti et al., 2026; Soliz et al., 2024). Polymer identification was primarily limited to particles larger than approximately 500 µm due to the detection constraints of ATR-FTIR. Particles smaller than this size were classified based on visual identification and are therefore considered as suspected microplastics.

2.3 Quality Control and Contamination Prevention (QA/QP)

Within the scope of the FTIR analyses, contamination prevention measures were applied in accordance with the general QA/QP protocol adopted throughout the study (Gündoğdu et al., 2025; Shune Thar et al., 2025). Prior to analysis, all glassware and laboratory equipment were rinsed three times with ultrapure

water and subsequently cleaned with acetone to minimize the risk of external particle contamination. The ATR (Attenuated Total Reflectance) crystal (e.g., diamond/Ge/ZnSe) used during FTIR measurements was carefully cleaned with acetone or ethanol before and after each run to ensure that no residual particles, oils, or surface films were present (Käppler et al., 2018; Villegas-Camacho et al., 2025). Background spectra were recorded prior to each analytical session to verify instrument stability and spectral accuracy. All solutions used during the preparation stages were vacuum filtered through 1.2 µm GF/C Whatman filter paper, and sample containers were sealed with aluminum foil during storage and handling to prevent airborne particle deposition (Käppler et al., 2018; Serranti et al., 2026). All procedures were carried out inside an ESCO enclosed laminar flow cabinet, and work surfaces were cleaned with acetone before and after each analytical sequence. This protocol was implemented to enhance the reliability of FTIR-based polymer identification and ensure the accuracy and reproducibility of the spectral results obtained for microplastic samples (Liu et al., 2024; Shune Thar et al., 2025). Procedural blanks were processed in parallel with samples, and no microplastic particles were detected. Quality assurance procedures such as recovery efficiency tests were not performed in this study.

2.4 Statistical Analysis

The normal distribution of the data was tested using Shapiro–Wilk test (Gurski & Dittel, 2026; Mukherjee & Bhonge, 2025). The abundance data did not show a normal distribution, thus Kruskal–Wallis test was employed to compare the abundance among the seasons (Alarfaj, 2026). Following a significant K-W test result Dunns test was used for pairwise comparisons to determine the differing seasons (Hsu et al., 2025). The microplastic size data was normally distributed. ANOVA was used to test the size among the stations. Tukeys HSD was used for pairwise comparisons following the ANOVA (Wilcox, 2022). Polymer, shape and color composition of MPs among the seasons were analyzed using non-metric dimensional scaling (NMDS) and PERMANOVA (Garrido-Martín et al., 2023; Jia et al., 2024). Non-metric multidimensional scaling (NMDS) ordination was performed based on Bray–Curtis dissimilarity matrices to visualize seasonal variations in microplastic polymer composition, shape, and color. The data were expressed in mean ± standard error of the mean. Statistical analyses were conducted using a confidence level of 95%. R programming language (ver. 4.5.2) was used for statistical analysis (R Core Team, 2024).

3 Results

3.1 Abundance and Concentration of MPs

Considering all sampling stations and seasons, overall mean microplastic concentrations of 5.4 MPs/L in surface waters and 348 MPs/kg in sediments were determined. Seasonal evaluation indicated pronounced temporal variability in MPs concentrations in both water and sediment samples. During the autumn season, sediment microplastic levels ranged between 8 and 16 MPs/kg, with an overall mean concentration of 12 ± 2.59 MPs/kg. In the same period, surface-water concentrations varied from 0.20 to 0.47 MPs/L, yielding an average value of 0.31 ± 0.10 MPs/L. In spring, sediment concentrations ranged from 12 to 32 MPs/kg, and the mean level was determined as 16.67 ± 7.80 MPs/kg. MPs concentrations in spring water samples fluctuated between 0.067 and 0.40 MPs/L, with a mean concentration of 0.22 ± 0.11 MPs/L. In summer, sediment microplastic levels were recorded within the range of 8–24 MPs/kg, and the average concentration was calculated as 14.66 ± 5.46 MPs/kg. Summer surface-water samples contained between 0.13 and 0.40 MPs/L, with a mean value of 0.22 ± 0.10 MPs/L. In winter, MPs concentrations in sediments ranged from 12 to 20 MPs/kg, with an average level of 14.66 ± 3.20 MPs/kg. Winter water samples exhibited comparatively lower concentrations, varying between 0.13 and 0.20 MPs/L, and the overall mean concentration was determined as 0.14 ± 0.02 MPs/L. Overall, MPs accumulation in sediments was consistently higher and more variable than in the aquatic environment, suggesting that particle adhesion, settling processes, and depositional dynamics play a dominant role in controlling microplastic distribution (Fig. 2). Evaluation of the spatial distribution revealed that the highest microplastic concentration in sediment samples was observed at station B6, whereas the lowest MPs levels were recorded at stations B1 and B4. In contrast, surface-water samples exhibited a different

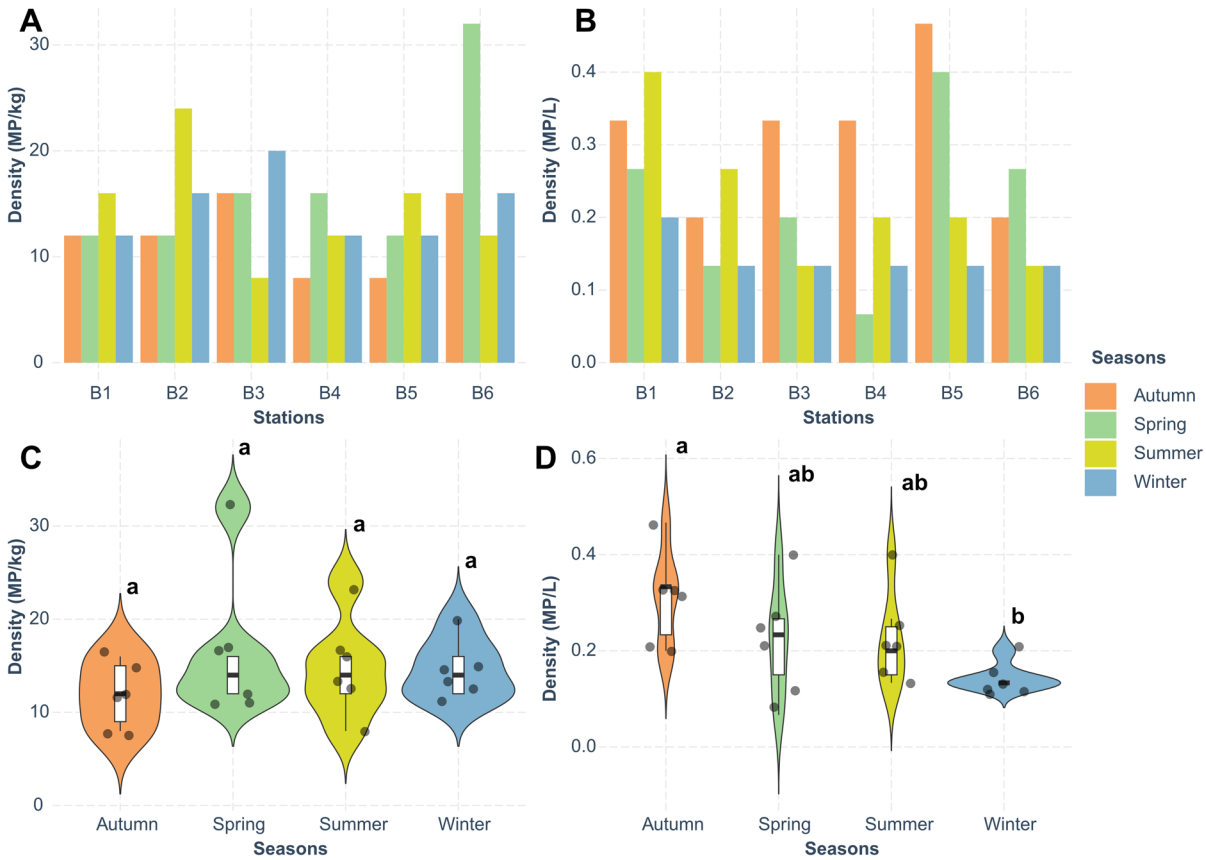


Fig. 2 Station-based and seasonal variation of microplastic (MPs) concentrations in the study area. **A**: presents MPs levels in sediments according to sampling stations, **B**: shows MPs concentrations in surface waters by stations, **C**: provides the statistical evaluation of seasonal MPs distribution in sediments, and D: illustrates the statistical assessment of seasonal MPs variation in surface waters

pattern: the highest microplastic concentrations were determined at stations B1 and B5, while the lowest values were detected at stations B2 and B6 (Fig. 2).

Statistical comparisons among seasons showed that microplastic concentrations in sediments did not differ significantly (Kruskal Wallis test, $p > 0.05$). However, significant seasonal differences were observed in surface-water samples, particularly between the autumn and winter seasons (Kruskal Wallis test, $p < 0.05$) (Fig. 2).

3.2 Polymer-Based Characterization of MPs

Polymer composition data presented in the supplementary datasets demonstrate the proportional distribution of detected MPs and provide a quantitative basis for the interpretation of Fig. 3. According to the overall polymer assessment, PETG represented the most abundant polymer type with 20.83% (n = 35), followed by PP with 11.31% (n = 19), and ABS and PA each contributed 10.12% (n = 17). PE accounted for 9.52% (n = 16), while PAN constituted 8.33% (n = 14). Less common polymers included PC (7.74%), PET (5.95%), POM (4.76%), and PVC (4.17%). This overall structure indicates that microplastics in the Borçka Reservoir were dominated by polymers widely associated with consumer plastics and packaging materials (Fig. 3).

Seasonal and sample-type–based evaluation further clarified spatial and temporal patterns. In autumn sediment samples, PAN and PA were dominant, each comprising 16.67%, with ABS and PP each accounting for 11.11% of the particles. Spring sediment samples showed a strong prevalence of

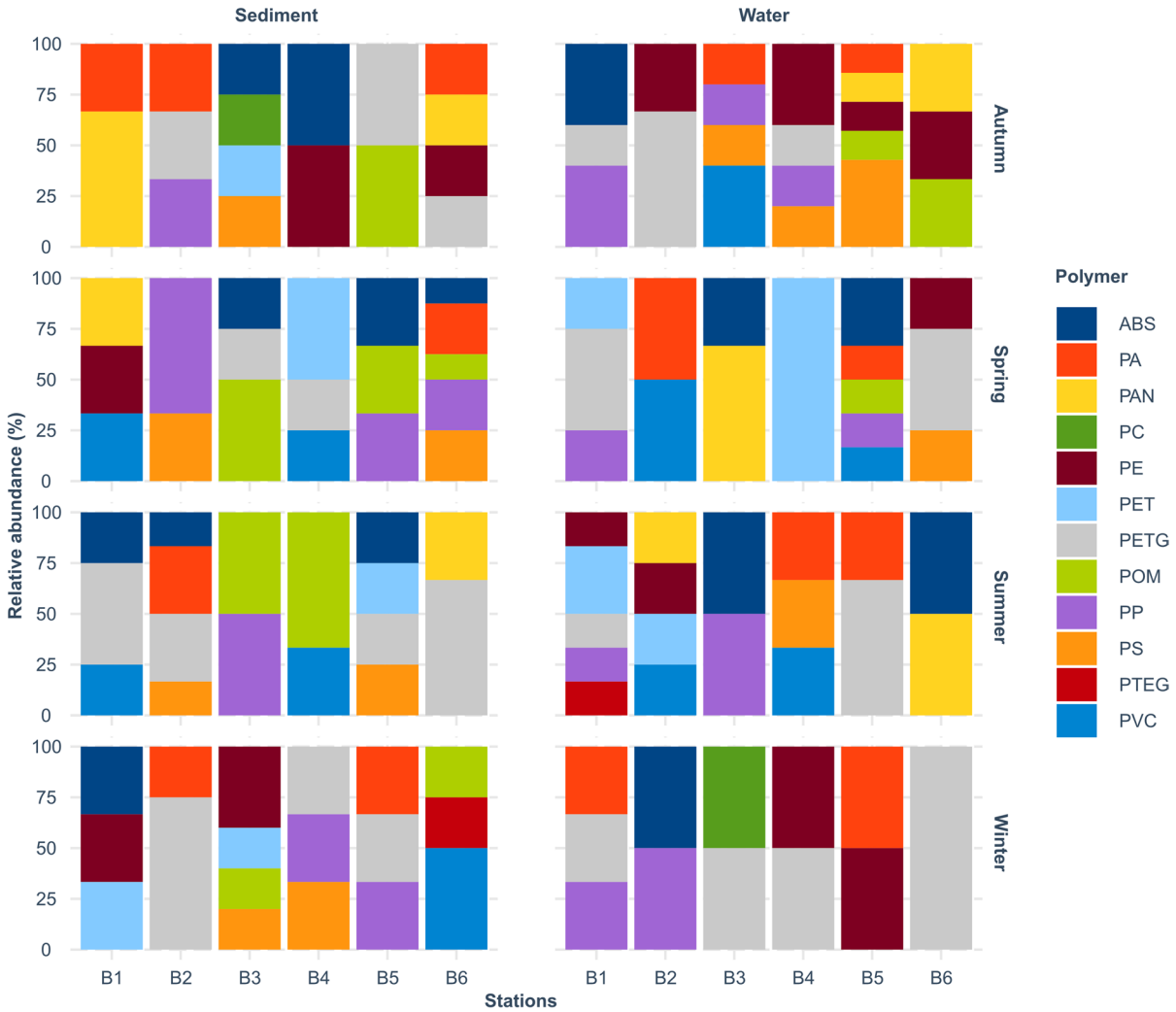


Fig. 3 Percentage distribution of MPs polymer types by stations and seasons

ABS (32.14%) and PA (21.43%), whereas in summer sediments ABS remained dominant (25.81%) followed by POM (16.13%) and PET (12.90%). Winter sediment samples were characterized mainly by PETG (28.57%) and PA (21.43%).

Water samples exhibited comparatively different seasonal compositions. Autumn surface waters were dominated by PETG (26.32%) and PVC (21.05%), while winter waters showed PE as the leading polymer type with 33.33% followed by PP with 20.00%. In spring waters, PETG (28.57%) and PA (25.00%) were most common. Summer water samples were largely composed of PETG (31.58%) and PA (21.05%).

When evaluated across the entire study area and all seasons, the results confirm that stations influenced by settlements and stream inputs contained relatively higher proportions of PETG, ABS, and PA polymers, whereas more distant stations with limited human impact exhibited greater contributions from PE and PP polymers. The persistence of PETG and PA dominance in water samples throughout all seasons indicates that microplastics are continuously supplied from land-based sources. In sediments, the variability observed in polymers such as POM, PVC, and PET suggests that microplastic accumulation is largely controlled by seasonal settling and depositional processes. Furthermore, the fact that

polymer composition exhibits station-specific characteristics and shows pronounced seasonal differentiation between the water column and the sedimentary environment demonstrates that microplastics display a distinct distribution pattern in both spatial and temporal terms.

3.3 Shape-Based Classification and Characterization of MPs

Shape-based evaluation of detected microplastics in sediment and water samples is presented in Fig. 4. Integrated analysis of the supplementary datasets revealed that the physical form distribution of microplastic particles exhibited considerable spatial and seasonal variability within the reservoir ecosystem. Overall assessment across all stations, seasons, and sample types indicated that fragments were the most common MPs shape, accounting for 38.10% (n = 64) of the total particles. This was followed by fibers with 35.12% (n = 59) and films with 26.79% (n = 45).

Seasonal patterns showed distinct differences between environmental compartments. In autumn sediment samples, MPs shapes were distributed as 38.89% films (n = 7), 33.33% fragments (n = 6), and 27.78% fibers (n = 5), with a mean concentration of 12.00 ± 2.59 MPs/kg. In contrast, autumn surface-water samples had an average microplastic level of 0.31 ± 0.10 MPs/L, dominated mainly by fragments

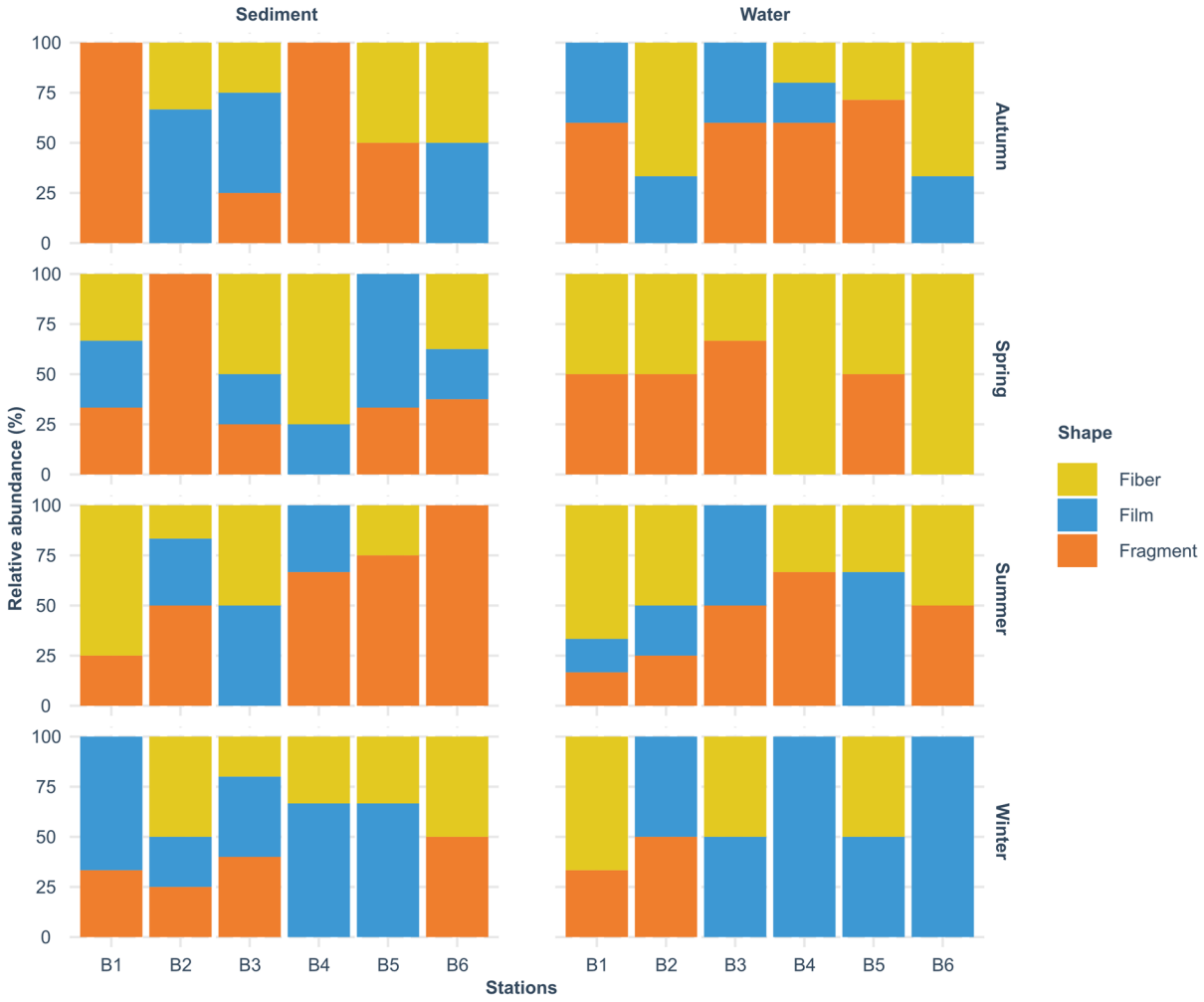


Fig. 4 Percentage distribution of MPs shape types by stations and seasons

(40.00%), while fibers and films each contributed 25.00%.

During the spring season, sediment samples contained between 12 and 32 MPs/kg, and the average concentration was determined as 16.67 ± 7.80 MPs/kg. Summer sediment concentrations ranged from 8 to 24 MPs/kg, with a mean level of 14.66 ± 5.46 MPs/kg. Winter sediment samples showed MPs levels varying from 12 to 20 MPs/kg and an overall average of 14.66 ± 3.20 MPs/kg.

Seasonal concentrations in surface waters were comparatively lower. Winter water samples contained between 0.13 and 0.20 MPs/L, yielding an average of 0.14 ± 0.02 MPs/L. In summer waters, concentrations varied from 0.13 to 0.40 MPs/L, with a mean value of 0.22 ± 0.10 MPs/L, while spring waters exhibited levels between 0.067 and 0.40 MPs/L and an average of 0.22 ± 0.11 MPs/L.

Spatial evaluation among stations was fully consistent with the shape overall and shape by station datasets. The findings confirmed that stations influenced by settlements and stream inputs exhibited relatively higher proportions of fiber and films, whereas more distant stations with limited human pressure were characterized predominantly by fragment-type microplastics. These results demonstrate that microplastic distribution in the Borçka Reservoir is largely governed by continuous anthropogenic inputs and season-dependent transport and depositional processes.

3.4 Color Classification of MPs

In this study, detected MPs particles were visualized proportionally according to color categories in Fig. 5. Overall evaluation indicated that transparent/colorless microplastics constituted the most prevalent color group, accounting for 21.43% (n = 36) of all particles. This was followed by blue-colored particles with 20.83% (n = 35) and orange microplastics with 19.64% (n = 33). Black, red, and green microplastics were recorded at proportions of 11.90% (n = 20), 10.71% (n = 18), and 10.12% (n = 17), respectively. The lowest contribution was observed in the grey color group with 5.36% (n = 9). Spatial assessment revealed that water samples from stations B1 and B5, located close to settlements and stream inputs, contained relatively higher proportions of blue and transparent microplastics. In contrast, stations B2 and B6, characterized by limited human influence, exhibited lower percentages of colored microplastics. Sediment samples displayed a more heterogeneous pattern; transparent MPs were dominant in winter water samples (33.33%), whereas blue particles showed an increased proportion in summer sediments (22.73%). Integration of all results confirms that the color distribution of microplastics in the reservoir is largely affected by local anthropogenic activities and seasonal transport and depositional processes. The persistence of transparent and blue MPs across most stations and seasons supports the interpretation that plastics associated with packaging materials, textile-derived fibers, and fishing-related sources represent continuous and stable inputs to the Borçka Reservoir Ecosystem.

3.5 Characterization and Classification of MPs According to Size

Microplastic particle sizes detected in sediment and surface-water samples were statistically evaluated according to stations and seasons in Fig. 6. In autumn sediment samples from station B1, microplastic sizes ranged from 500 to 1370 µm, with a mean particle size of 812.85 ± 253.82 µm. Autumn water samples from the same station exhibited a broader range between 530 and 2950 µm, yielding an average size of 1397.72 ± 660.32 µm. At station B2, sediment MPs sizes varied from 300 to 2100 µm and the mean size was determined as 983.25 ± 513.61 µm, while microplastics in autumn waters ranged between 360 and 1462 µm, with an overall mean of 771.36 ± 335.76 µm. Sediment samples collected in autumn at station B3 contained particles between 380 and 2560 µm and averaged 1147.87 ± 673.07 µm; surface waters from this station showed sizes from 340 to 2600 µm and a mean of 1243.33 ± 694.10 µm. At station B4, sediment MPs sizes ranged from 360 to 2300 µm, with an average particle size of 1011.50 ± 647.65 µm whereas autumn water samples contained particles between 390 and 2600 µm and averaged 1130.00 ± 625.83 µm. The highest mean MPs size in sediments was observed at station B5 during autumn, where sizes varied from 640 to 3310 µm and the mean size was calculated as 1631.67 ± 804.49 µm. In contrast, autumn water samples from station B5 were comparatively smaller, ranging from 460 to 1680 µm and averaging 942.78 ± 356.20 µm. At station B6,

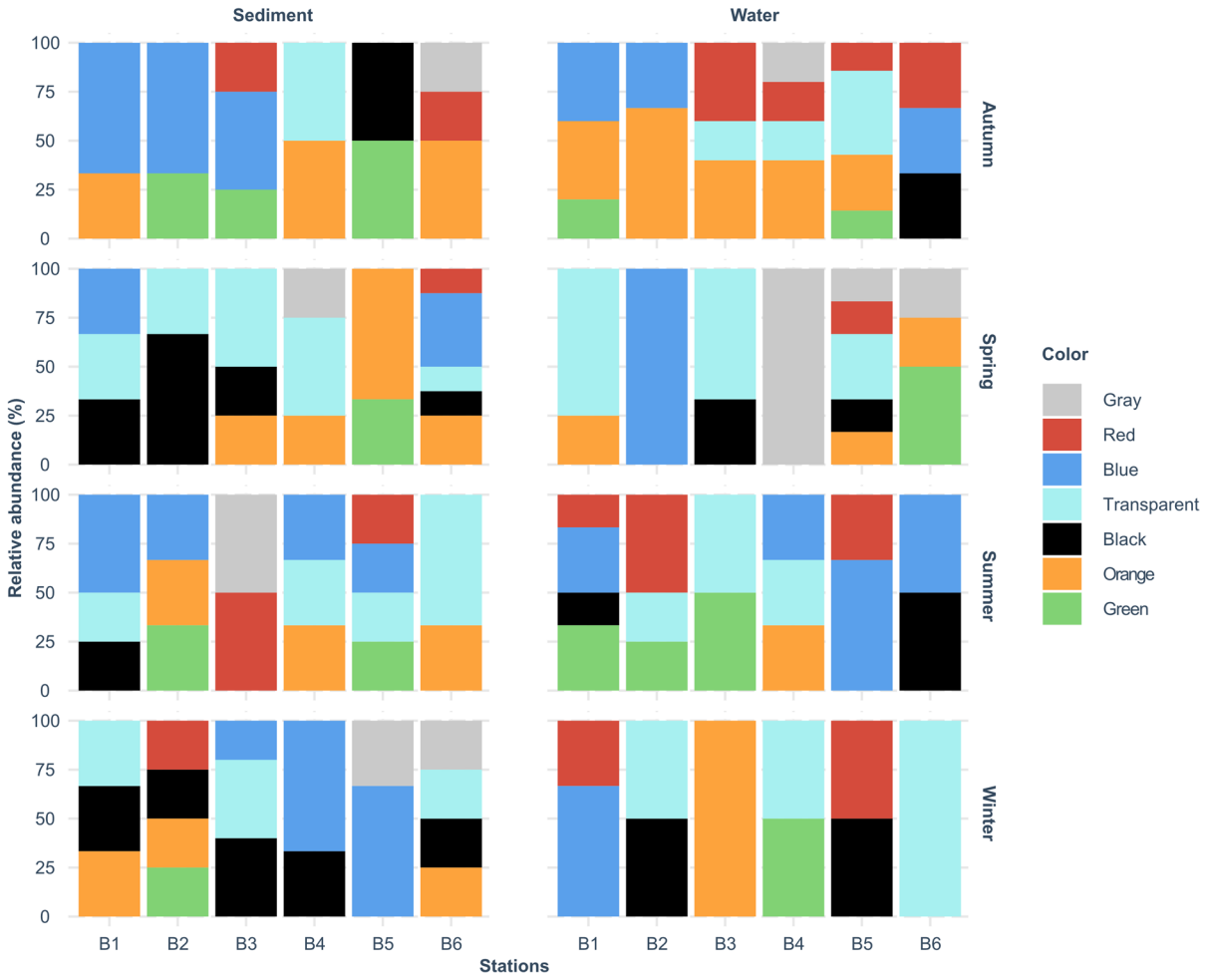


Fig. 5 Percentage distribution of MPs color types by stations and seasons

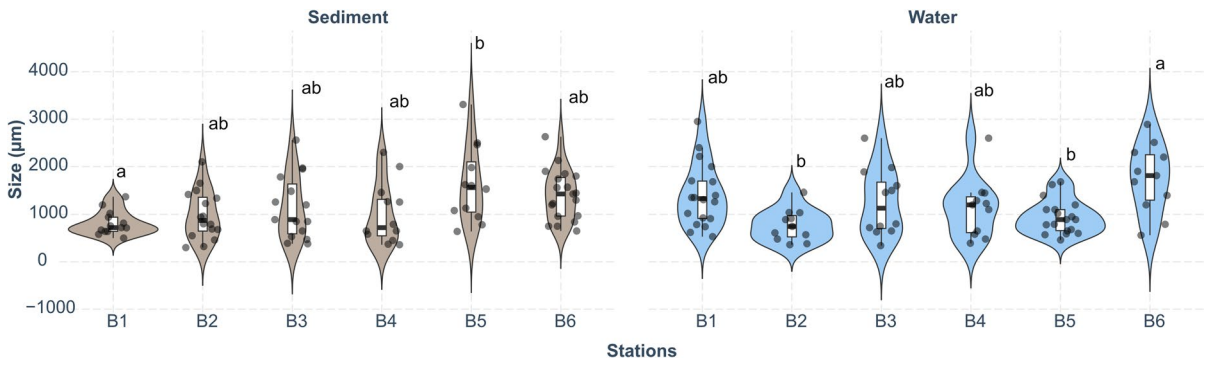


Fig. 6 Violin–boxplot representation of particle size distributions in sediment and water samples across sampling stations (B1–B6). Boxes indicate the interquartile range with median values, while individual points represent raw data. Different lowercase letters **a**, **b** denote statistically significant differences among stations within each matrix (sediment or water) based on non-parametric post hoc comparisons ($p < 0.05$)

sediment MPs ranged between 650 and 2630 µm and showed an average size of 1405.79 ± 527.56 µm, while MPs in autumn waters from this station varied from 560 to 2890 µm, with a mean particle size of 1749.09 ± 719.44 µm. Spatial and seasonal comparisons indicate that MPs particles in the water column were generally larger and more variable than those accumulated in sediments, suggesting that fragmentation processes and selective settling dynamics play a fundamental role in controlling MPs size distribution within the Borçka Reservoir Ecosystem.

Statistically significant differences in particle size were observed among stations in both sediment and water samples ($p < 0.05$) (Fig. 6). In sediment samples, a significant difference was detected between stations B1 and B5, whereas no significant differences were found between B1 and stations B2, B3, B4, and B6, nor between B5 and these intermediate stations. This pattern indicates partial spatial differentiation in sediments, without a complete separation among all stations. In contrast, water samples showed a clearer spatial structure, with station B6 differing significantly from stations B2 and B5, while no significant differences were observed between B6 and stations B1, B3, and B4. Likewise, no statistically significant differences were detected among the intermediate water stations.

3.6 Seasonal Patterns of Microplastic Composition Revealed by NMDS Analysis

Non-metric multidimensional scaling (NMDS) analysis clearly revealed seasonal patterns in MPs polymer type, shape, and color composition in both sediment and water samples. In the polymer-based NMDS ordinations (Fig. 7A–B), sediment samples exhibited substantial seasonal overlap, indicating relatively limited seasonal variability, whereas water samples showed a more pronounced seasonal separation, suggesting higher temporal variability in polymer composition. Shape-based NMDS results (Fig. 7C–D) demonstrated that seasonal groupings in sediments largely overlapped, while several seasons in water samples were spatially separated, reflecting season-dependent changes in particle morphology. Similarly, color-based ordinations (Fig. 7E–F) showed compact seasonal clustering in sediments but a wider seasonal dispersion in water samples, indicating that seasonal variability in color composition was more evident in the water column. Overall, the results indicate that seasonal variation in MPs characteristics is more pronounced in water samples than in sediments.

4 Discussion

4.1 Spatiotemporal Patterns of MPs Abundance in Borçka Reservoir (Water and Sediment)

MPs contamination was evident throughout Borçka Reservoir, with clear differences between environmental compartments and discernible spatial–seasonal variability. In surface waters, seasonal mean concentrations range from 0.14 ± 0.02 MPs/L in winter to 0.31 ± 0.10 MPs/L in autumn, while spring and summer values remained comparatively stable at approximately 0.22 MPs/L. In sediments, the pooled dataset integrating all stations and seasons yielded a cumulative abundance of 348 MPs/kg, whereas seasonal mean concentrations varied within a narrower range, from 12.0 ± 2.59 MPs/kg (autumn) to 16.67 ± 7.80 MPs/kg (spring). The consistently greater accumulation in sediments relative to the water column supports the role of reservoir depositional environments as effective sinks, where settling, particle–sediment interactions, and prolonged retention can integrate microplastic inputs over time (Mutlu et al., 2024, Gao et al., 2025).

Spatially, MPs abundance displayed contrasting station-level patterns between matrices, emphasizing the importance of hydrodynamic sorting and deposition processes in addition to source proximity (Paray et al., 2025). Sediment concentrations peaked at station B6, while the lowest levels occurred at stations B1 and B4. In surface waters, the highest concentrations were recorded at stations B1 and B5, whereas stations B2 and B6 showed comparatively lower values. Such matrix-dependent spatial differences indicate that microplastic distribution is governed not only by local anthropogenic pressures (e.g., settlements, tributary inflows, shoreline use) but also by residence time in the water column, selective settling, and potential resuspension, which can decouple water–sediment signals at specific locations (Paray et al., 2025; Raju et al., 2023; Wang et al., 2023; Xiang et al., 2025; Zhao et al., 2026a, 2026b).

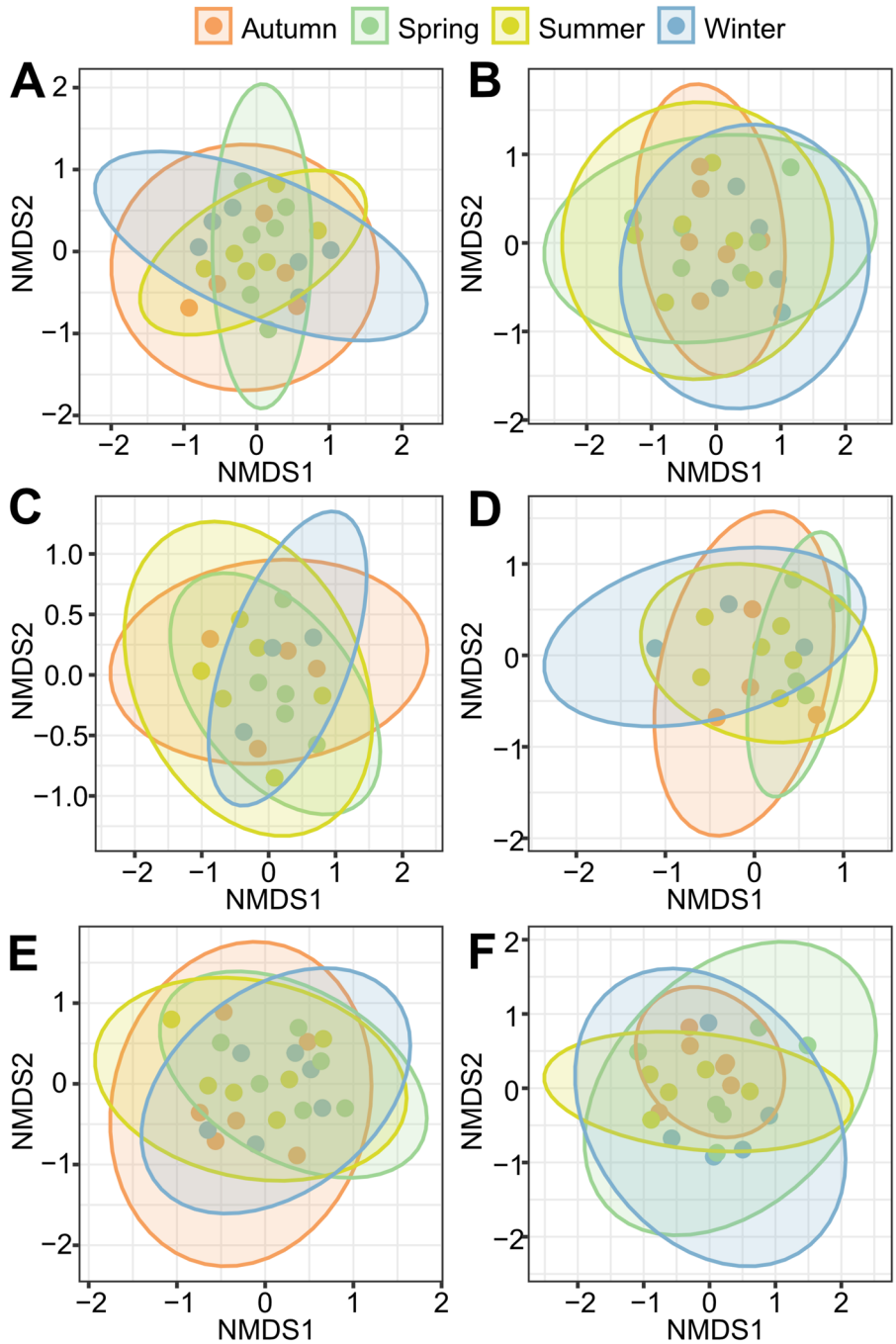


Fig. 7 Non-metric multidimensional scaling (NMDS) ordinations illustrating seasonal variations in MPs polymer type, shape, and color composition in sediment and water samples. Panels **A**–**B** represent polymer type, panels **C**–**D** particle shape, and panels **E**–**F** particle color. Left panels (A, C, E) correspond to sediment samples, while right panels (B, D, F) represent water samples

Seasonal statistics further highlighted compartment-specific dynamics. Sediment concentrations did not differ significantly among seasons (Kruskal–Wallis, $p > 0.05$), consistent with sediments functioning as an integrative archive that dampens short-term fluctuations. In contrast, surface-water concentrations exhibited significant seasonal variation ($p < 0.05$), with the most pronounced difference observed between autumn and winter. This pattern suggests that the water column responds rapidly to seasonal forcing, such as precipitation-driven runoff, hydrological connectivity, and seasonal changes in human

activities, whereas sedimentary microplastics reflect longer-term accumulation and mixing processes (Li et al., 2023, Valsan et al., 2024, Akdemir et al., 2025, Fonseca et al., 2025). Collectively, these results demonstrate that Borçka Reservoir operates as both a dynamic transport medium in the water column and a long-term storage compartment in sediments, underscoring the value of matrix-specific monitoring when assessing MPs pollution in reservoir ecosystems. In addition to local anthropogenic activities, atmospheric deposition and precipitation-driven surface runoff may also contribute to the observed microplastic inputs in Borçka Reservoir. Atmospheric transport of microplastic particles has been increasingly recognized as an important pathway introducing plastics into remote aquatic environments. During precipitation events, airborne particles can be scavenged from the atmosphere and deposited directly into the water surface or transported into the reservoir through surface runoff from surrounding catchments. In reservoir systems located within mountainous basins, such as the Çoruh River catchment, rainfall-induced runoff may mobilize plastic debris from urban areas, roads, agricultural lands, and riverbanks, subsequently delivering fragmented particles into the lake. Although precipitation data were not explicitly incorporated into the present analysis, these processes likely contribute to the seasonal variability observed in microplastic abundance and composition in the water column.

4.2 Morphological, Size, Color, and Polymer Characteristics of MPs

The integrated evaluation of MPs morphology, size, color, and polymer composition provides a comprehensive perspective on both the sources and environmental behavior of microplastics in Borçka Reservoir. Rather than representing independent attributes, these characteristics collectively reflect the fragmentation history, transport pathways, and potential ecological interactions of microplastics within the reservoir system (Ziajahromi et al., 2024, Fonseca et al., 2025).

In terms of morphology, fragment-type MPs constitute the dominant category (38.10%), followed closely by fibers (35.12%) and films (26.79%). The predominance of fragments suggests that secondary microplastics derived from the breakdown of larger plastic debris represent a major component of the contamination profile. In reservoir environments, fluctuating water levels, mechanical abrasion, ultraviolet exposure, and fluvial transport are known to accelerate the fragmentation of macroplastics, promoting the formation of irregular fragments (Lewanska & Barczynska, 2025; Ziajahromi et al., 2024). The increased contribution of fragments in surface waters during certain seasons, particularly autumn, is likely to reflect enhanced runoff and tributary inflows transporting relatively fresh plastic debris into the lake (Julienne et al., 2019).

Fibers were especially prominent at stations influenced by settlements and stream inputs, indicating a strong contribution from textile-derived microfibers, fishing gear, and wastewater-related sources (Duong et al., 2023; Feng et al., 2025; Ghasemi et al., 2023). This pattern is consistent with observations from other inland waters in Türkiye, where fibers are frequently reported as dominant or co-dominant microplastic forms (Gündoğdu et al., 2023, 2025; Korkmaz et al., 2026; Pehlivan & Gedik, 2021). Additionally, the aquaculture facilities in the dam lake can be another source of fibers, since the polymer ropes used in aquaculture facilities release plastics (Yandi et al., 2026).Ecologically, fibers are of particular concern due to their elongated and flexible structure, which facilitates ingestion by planktonic organisms, benthic invertebrates, and fish, potentially leading to physical irritation and reduced feeding efficiency (Kim et al., 2024; Yao et al., 2021). Film-type MPs, commonly associated with packaging materials and thin plastic sheets, were more abundant in sediments during specific seasons (e.g., autumn), suggesting preferential settling of low-density, high-surface-area particles following prolonged suspension in the water column (Verma et al., 2025).

MPs size distributions further elucidated transport and accumulation mechanisms within the reservoir (Uurasjärvi et al., 2020). Particle sizes in sediments were generally more constrained (812–1632 µm) compared to those in surface waters (771–1749 µm), where a broader size spectrum and higher variability were observed. This pattern indicates selective deposition of smaller and denser particles into sediments, while larger and less fragmented microplastics remain suspended or are intermittently transported within the water column (Uurasjärvi et al., 2020, Caputo et al., 2021). From an ecological perspective, the dominance of particles within the 1–2 mm size range represents a critical exposure window for a wide range of aquatic

organisms, particularly benthic and filter-feeding taxa. Accordingly, size distributions in this study are interpreted as indicators of potential biological availability rather than direct measures of toxicological impact.

Color composition offered additional insight into both source characteristics and environmental aging processes (Horie et al., 2024). Transparent/colorless (21.43%) and blue (20.83%) microplastics were the most abundant across the reservoir. Transparent particles are commonly linked to packaging materials and thin plastic films that lose pigmentation during prolonged environmental exposure, whereas blue microplastics are frequently associated with fishing-related materials, ropes, nets, and textile fibers (Chang et al., 2024; Horie et al., 2024; Sahai et al., 2025). Seasonal and spatial variability in color composition, especially within the water column, suggests continuous and ongoing inputs rather than episodic contamination events (Chang et al., 2024). Importantly, colored microplastics may increase the likelihood of ingestion by visually oriented organisms, thereby enhancing the potential for trophic transfer. However, color attributes were interpreted in conjunction with morphology and polymer composition, rather than as standalone indicators of source origin (Li et al., 2024; Niu et al., 2026; Xiang et al., 2026).

Polymer composition revealed a diverse assemblage reflecting both domestic and industrial plastic usage within the catchment (Bond et al., 2018). PETG (20.83%) emerged as the dominant polymer, followed by PP (11.31%), ABS (10.12%), and PA (10.12%), with substantial contributions from PE (9.52%) and PAN (8.33%). Consumer-related polymers such as PETG and PP suggest significant inputs from packaging and household products, while the presence of ABS, PA, and PAN points to industrial, automotive, and electronic sources transported at the basin scale (Afzal et al., 2024; Erni-Cassola et al., 2019). Seasonal contrasts between matrices further emphasized the role of environmental processes: sediment polymer composition varied seasonally in response to deposition and resuspension dynamics, whereas surface waters exhibited persistent dominance of PETG and PA, indicating sustained land-based inputs throughout the year (Debroy et al., 2022, Sharma, et al. 2024a, 2024b, Pal et al., 2025, Kalangutkar et al., 2026).

When considered collectively, the morphological, size-based, color, and polymer characteristics demonstrate that microplastic contamination in Borçka Reservoir is not only quantitatively significant but also qualitatively complex. The coexistence of multiple shapes, size classes, colors, and polymer types highlights the influence of diverse anthropogenic activities and dynamic environmental processes. This integrated characterization underscores the importance of multidimensional approaches in microplastic research, as single-parameter assessments may underestimate both the ecological relevance and management implications of microplastic pollution in freshwater reservoir ecosystems. The observed differences in polymer composition between sediment and water samples can also be interpreted in relation to the intrinsic density of polymer types and hydrodynamic transport processes operating within the reservoir. Polymers such as PE and PP possess relatively low densities (< 1 g cm^{-3}) and therefore tend to remain suspended in the water column for longer periods, particularly under conditions of turbulence and hydrodynamic mixing. In contrast, relatively denser polymers such as PET, PVC, and ABS are more likely to sink and accumulate within sediments through gravitational settling. In reservoir systems, MPs transport is additionally influenced by physical processes such as turbulence, dispersion, and diffusion, which can redistribute particles both vertically and horizontally within the water column. Furthermore, episodic hydrodynamic disturbances, including inflow events and sediment resuspension, may reintroduce previously deposited MPs into the water column. These processes collectively contribute to the spatial and matrix-specific differences observed in polymer composition in Borçka Reservoir.

4.3 Implications for Reservoir Ecosystems and Environmental Management

Overall, this study demonstrates that microplastic pollution in Borçka Reservoir exhibits marked spatial and seasonal variability, with particularly dynamic compositional changes in the water column. The integration of morphological, size-based, color, and polymeric characteristics reveals a heterogeneous contamination profile driven by continuous anthropogenic inputs.

From a management perspective, these results underscore the necessity of incorporating seasonal sampling into microplastic monitoring programs for reservoir ecosystems. Furthermore, the identification of high-hazard polymers such as ABS, PVC, and PAN suggests that mitigation efforts should prioritize controlling their sources within the catchment. Collectively, the findings provide a robust scientific basis for future monitoring, ecological risk assessment, and the development of targeted management strategies for freshwater reservoirs in Türkiye.

The comparison of microplastic (MPs) characteristics obtained in the present study with those reported from both national and international freshwater systems reveals clear similarities as well as site-specific differences in terms of abundance, size distribution, color, and polymer composition (Supplementary Table 2). Microplastic abundance in surface waters of the present study (0.14–0.31 MPs L^{-1}) is comparable to values reported for relatively low-to-moderately impacted freshwater environments, such as Karagöl Lake, Türkiye (0.5 MP $station^{-1}$)(Tatlı & Altunışık, 2025), Dongting Lake, China (0.62–4.31 MPs L^{-1})(Hu et al., 2020), and Lake Victoria, Uganda (0.02–2.19 MPs m^{-3})(Egessa et al., 2020), but markedly lower than those observed in heavily urbanized river systems such as the Cooum River, India (341 MPs $sample^{-1}$)(Afzal et al., 2024), and the Po River, Italy (0.03–12.7 items m^{-3})(Serranti et al., 2026). In contrast, sediment-associated MP abundances in the present study (8–32 MPs kg^{-1}) fall within the lower range of values reported for Turkish inland waters, yet are substantially lower than those documented for highly impacted systems such as the Çoruh River (>400 MPs kg^{-1}) (Akkan & Mutlu, 2022) and Dongting Lake sediments (21–52 MPs 100 g^{-1})(Hu et al., 2020), indicating a comparatively moderate accumulation pressure within the study area.

Across nearly all compared studies, microplastics smaller than 1–2 mm dominates both water and sediment compartments, highlighting the pervasive role of secondary fragmentation processes and prolonged environmental residence times. The predominance of transparent, blue, and black particles observed in the present study is consistent with patterns reported from a wide range of freshwater environments, including Dongting Lake, Lake Victoria, the Po River, and Brazilian river systems. Transparent particles are generally associated with weathered packaging materials and aged polyethylene, or polypropylene-based products, whereas blue and black particles are frequently linked to textile fibers, fishing-related activities, and urban-derived inputs. Similarly, the polymer composition identified in the present study, dominated by PETG, PP, PE, PA, and PAN, largely overlaps with those reported globally, where PE and PP consistently represent the most abundant polymer types due to their extensive use, low density, and high environmental persistence. The occurrence of relatively high-risk polymers such as PA, PAN, and PETG further suggests potential ecological implications, particularly given their association with higher chemical additive loads and enhanced pollutant sorption capacity. Overall, the close agreement between the present findings and those from both national and international studies indicates that the observed microplastic contamination reflects not only local anthropogenic pressures but also broader, globally consistent patterns of plastic production, usage, degradation, and transport in freshwater environments. This study is limited by the absence of biota analysis and by focusing only on surface sediments, which may underestimate deeper microplastic burial. In addition, although strict contamination control procedures were implemented during sample processing, advanced quality assurance procedures such as recovery efficiency tests were not conducted in this study. Therefore, the potential loss of microplastic particles during extraction cannot be completely excluded.

5 Conclusion

This study provides a comprehensive spatiotemporal assessment of microplastic pollution in Borçka Reservoir by integrating abundance data with detailed morphological, size-based, color, and polymeric characteristics. The results demonstrate that microplastics are ubiquitous throughout the reservoir ecosystem, with consistently higher accumulation in sediments compared to surface waters, confirming the role of reservoir environments as effective sinks for MPs retention. Seasonal variability was more pronounced in the water column, whereas sediments exhibited relatively stable concentrations, highlighting the contrasting temporal dynamics of pelagic and benthic compartments in semi-enclosed freshwater systems.

The dominance of fragment- and fiber-type microplastics, together with the prevalence of particles within the 1–2 mm size range, indicates that secondary microplastics derived from the fragmentation of larger plastic debris constitute the major component of contamination in the reservoir. Color distributions were dominated by transparent and blue particles, combined with polymer profiles characterized by PETG, PP, PE, PA, and PAN, reflect continuous land-based inputs associated with packaging materials, textile-derived fibers, fishing activities, and industrial sources within the Çoruh River Basin. These findings suggest that MPs contamination in Borçka Reservoir is not driven by isolated events but rather sustained by ongoing anthropogenic pressures coupled with hydrological transport and depositional processes.

Overall, the findings position Borçka Reservoir as both a sink and a secondary source of microplastics within the Eastern Black Sea Basin, emphasizing its strategic role in basin-scale microplastic transport pathways. From a management perspective, the results underscore the necessity of implementing long-term, seasonally resolved monitoring programs that simultaneously target water and sediment compartments. Mitigation strategies should prioritize the reduction of land-based input through improved wastewater treatment efficiency, control of industrial and urban runoff, and the regulation of fishing and recreational activities that contribute synthetic materials to the reservoir. In addition, the identification of potentially hazardous polymers highlights the need for polymer-specific management approaches, including restrictions on the use of high-risk plastics and the promotion of safer material alternatives within the catchment. Collectively, these measures will be essential for minimizing future microplastic accumulation, reducing ecological risk, and supporting sustainable management of freshwater reservoirs in Türkiye and comparable regions worldwide.

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Author Contribution **Koray ÖZŞEKER (KÖ):** Conceptualization, Methodology, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing **Bilal ONMAZ (BO):** Formal analysis, Investigation, Data Curation, Visualization, Writing—Original Draft, Writing—Review & Editing.

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Data Availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval This study did not involve human participants or animals. Therefore, ethical approval is not applicable.

Competing Interests The authors declare no competing interests.

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