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SEDIMENTS, SEC 2 • PHYSICAL AND BIOGEOCHEMICAL PROCESSES • RESEARCH ARTICLE

Distribution and interaction profiles of metal(loid)s and microplastics in lake sediments: Lake Iznik (NW Türkiye)

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Abstract

Purpose Sediments are often the first areas to be examined in order to understand the behavior, transport, transformation, and accumulation of pollutants in freshwater systems. This study was designed to determine: (1) the distribution, source, and ecological risks of metal(loid)s (Ms); (2) the polymer types, distribution, and ecological risks of microplastics (MP); and (3) the potential for microplastics to function as carriers of metal(loid) in Lake Iznik sediment.

Materials and Methods The concentrations of 14 selected metal(loid)s were determined by ICP-MS, the size and morphological characteristics of MPs were examined using a stereomicroscope, and polymer identification was performed using FTIR. The adsorption of Ms onto the MP surface was examined using SEM-EDX. The environmental risks of the detected Ms amounts in sediment were investigated using sediment quality guidelines and indices, along with multivariate statistical analyses.

Results and discussion Fe and Al were the elements with the highest concentrations in the sediment and As was the element posing the highest ecological risk. Al, Fe, and Mn were of geogenic origin, while Cd, Cu, and Zn were of anthropogenic origin, as supported by principal component, clustering, and correlation analyses. As, grouped with Ba and Sr and having the highest relative toxicity, was not detected on the surface of MPs, despite being the most abundant element in sediments along with Fe and Mn. Cationic metals such as Cd, Cr, Cu, Pb, and Zn were found to be adsorbed onto the surfaces of MPs.

Conclusion The findings demonstrate that the behavior of MPs, specifically their ability to selectively adsorb cationic metals while failing to bind with As oxyanions, is governed by chemical speciation and surface-level interactions within the water. This selectivity controls the distribution and potential mobility of Ms in lake sediments, providing significant data for environmental risk assessments.

Keywords Sediment quality · Arsenic speciation · Anthropogenic and geogenic sources · Microplastic · Metal(loid)

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1 Introduction

Sediments are systems that maintain the exchange of matter with the water column in freshwater ecosystems, thereby playing a role in the transport of pollutants into the food chain and organisms. Sediment toxicology is closely related to pollutants (metalloids (Ms), microplastics (MP), etc.) that have high toxicity and environmental persistence and interact easily with biological systems, based on these properties of sediments (Liu et al. 2021). Among these Ms, arsenic (As) holds a significant place due to its high toxicity, its ability to enter the food chain and be transported through trophic levels, and its sensitivity to environmental conditions under different oxidation states (Patel et al. 2023). In sediments, the binding and/or release of total As is directly linked to the sedimentary microbiota, redox conditions, organic matter, and Fe-Mn oxides (Couture et al. 2010; He et al. 2024). Therefore, even low concentrations of As at the sediment–water interface serve as a warning system indicating ecosystem health.

The adverse effects of As, one of the most dangerous environmental pollutants, on the cardiovascular, renal, respiratory, endocrine and immune systems have been demonstrated in previous studies (ATSDR 2007). Furthermore, these studies have documented that As causes epigenetic changes and carcinogenicity during embryonic development (Abdul et al. 2015). Ingestion is the most effective route of arsenic exposure. Therefore, the accumulation of arsenic in sediments is critical not only in environmental impact assessments but also in the investigation of biological impact values (Chung et al. 2014).

Due to their small size, large specific surface areas, and functional groups present on their surfaces, MP's (< 5 mm) can adsorb Ms and potentially act as vectors for their transport (Bi et al. 2024). This situation indicates that, in addition to examining the Ms quantity in sediment analyses, one must not overlook the portion that MP facilitates transport by adsorbing (Liu et al. 2021). In particular, As-MP interactions are a subject that has recently attracted the attention of ecotoxicological research, and there are only a limited number of studies on this topic.

Lake Iznik, an important freshwater ecosystem located in northwestern Turkey, is subject to dense settlement areas (and associated traffic pressure), agricultural activities, and recreational use (Köker 2022). All these pressures are activities that could contribute to the accumulation of Ms and MPs. However, studies addressing both issues in Lake Iznik sediments are also limited.

The main objectives of this study are: (1) to investigate the accumulation of microplastics in the sediments of Lake Iznik; (2) to assess potential ecological risks through sediment quality indices; (3) to determine the number of MP per station (abundance), polymer types, and morphological characteristics such as size, colour, and shape; and (4) to understand the potential for Ms transport via adsorption by determining the presence and amount (percentage) of Ms in the MP obtained from the sediment. In this context, the aim is to contribute to future monitoring studies by presenting a dataset on Ms–MP interactions in Lake Iznik sediment.

2 Materials and methods

2.1 Study area and sample collection

Covering an area of approximately 2,246 km² and reaching a maximum depth of 70 m, Lake Iznik is a large freshwater lake located in the north-west of Türkiye. The lake is fed by the Karasu and Solöz streams, as well as by karst systems and surface runoff. The only surface outflow of Lake İznik is through the Karsak Stream, which transports excess water to the Gemlik Gulf (Meşeli 2010; Kasapoğulları 2022).

Sediment sampling was conducted in September 2022. The coordinates of the sampling stations were recorded using a Global Positioning System (GPS), and the stations were subsequently mapped. Surface sediment samples (0–10 cm), representing recent anthropogenic inputs, were collected from 25 stations using an Ekman grab sampler and a stainless-steel spatula (Suppl. Table 1, Fig. 1).

2.2 Metal(loid) analysis

Sample digestion and elemental analyses were performed by Bureau Veritas Mineral Laboratories, Canada (ACME LAB.) using ICP-MS according to the AQ270 analytical protocol. The results of replicate analyses, certified reference materials, procedural blanks, and method detection limits are presented in Suppl. Table 2. Elemental concentrations obtained from sediments collected at the 25 sampling stations around Lake İznik and their corresponding evaluations are presented in Table 1. Although several elements (Mo, Ag, U, Au, Th, Sr, Bi, Ti, B, W, Sc, Tl, S, Hg, Se, Te, and Ga) were analyzed, they were excluded from further evaluation because their concentrations were below the analytical detection limits in the majority of samples (detection limits: 0.01, 0.02, 0.1, 0.002, 0.1, 0.5, 0.5, 0.02, 1, 1, 20, 0.1, 0.1, 0.02, 20, 0.05, 0.1, 0.02, and 0.1 ppm, respectively). Accordingly, the metal(loid)s evaluated and discussed in this study include Al, As, Ba, Cd, Co, Cr, Cu, Fe, La, Mn, Ni, Pb, Sr, and Zn.

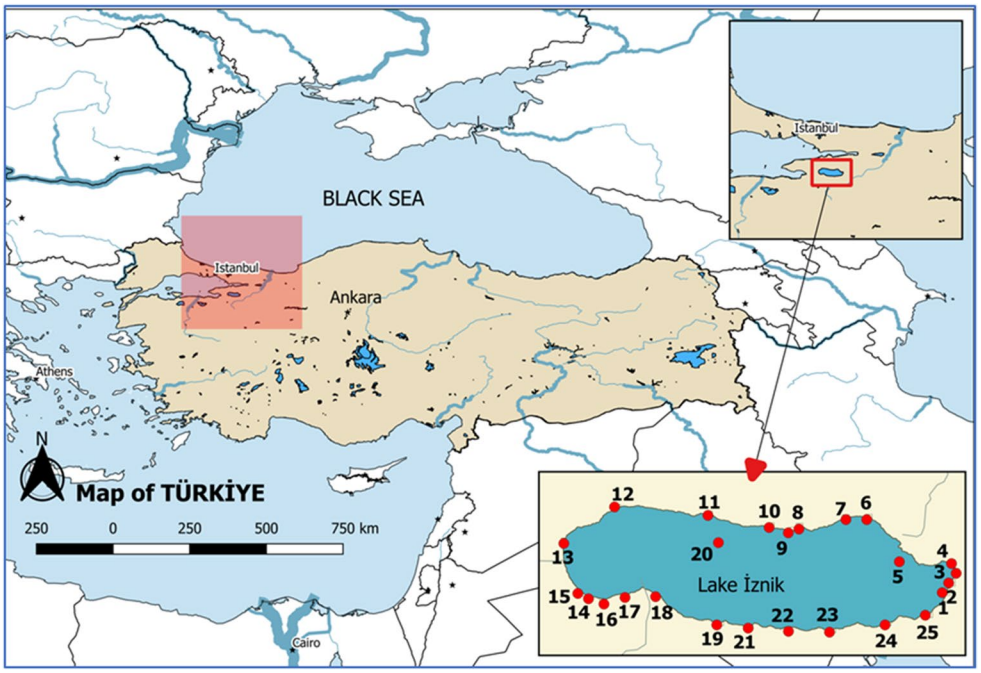


Fig. 1 Lake Iznik stations

2.3 Sediment quality assessment methods (SQGs)

Sediment quality guidelines (SQGs) are designed to assess environmental contamination and potential biological risks by comparing measured metal(loid) concentrations in sediments with natural background levels and ecotoxicological threshold values. Metal(loid) concentrations measured below the Effects Range–Low (ERL, Long and Morgan 1991) and Threshold Effect Level (TEL, Smith et al. 1996) guideline values are generally associated with a low probability of adverse biological effects on benthic organisms. The median effect range (MER; Long and Morgan 1991) and potential effect level (PEL; Smith et al. 1996) values are concentrations at which toxic effects are observed on the organism (Ouchir et al. 2016). Amounts below the ERL value are expected to affect less than 10% of organisms, while amounts exceeding the ERM value are expected to adversely affect more than 50% of organisms (Abrahim et al., 2008). In this study, the potential ecological risks posed by Ms were evaluated using sediment quality indices (contamination factor (CF), enrichment factor (EF), geoaccumulation index (Igeo), and toxic unit (TU) indices) (Ergen 2020). Earth crust values were used for average background reference values (Turekian and Wedepohl 1961).

2.4 Extraction and determination of microplastics

All glassware and equipment used in the experiment were rinsed with distilled water prior to use to minimize contamination. Sediment samples were dried at 60 °C for 24 h to stabilize their weight. A 30 mL solution of 30% hydrogen peroxide (H_2O_2) was added to 200 g of dried sediment sample placed in glass beakers and incubated at room temperature for 3 h to digest the organic matter contained therein. Subsequently, the samples were heated for a further 12 h at 50 °C, thereby increasing the oxidation of the residual organic matter. Subsequently, 300 mL of zinc chloride ($ZnCl_2$) solution solution (436 $\mathrm{g\,L^{-1}} \approx 1.6$–$1.7$ $\left(\mathrm{m^3}\right)^{-1}$) was added to the samples for the process of separating the MP from high-density minerals. This enabled the recovery of both low- and high-density polymers. The samples in the solution were stirred for 10 min and then left for 24 h for precipitation to occur. The density separation procedure was repeated three times to ensure MP recovery. The resulting supernatants were filtered using a 0.45 µm glass fiber membrane. After filtration, the membranes were placed in clean glass Petri dishes and left to dry at room temperature. All methods applied are based on protocols reported in the literature that are validated and widely used (Coppock et al. 2017). These methods were selected to ensure the reliability of MP abundance between stations and to enable methodological comparisons with previous studies.

2.5 Characterization of microplastics and polymer identification

The morphological characteristics (shape, color, and size) and abundance of MP were determined using a stereomicroscope (Leica S6 D). Polymer characterization was performed on particles morphologically identified as MP using Fourier Transform Infrared (FTIR) spectroscopy (Shimadzu

Table 1 Metal(loid) quantities and limit values in the sediment of Lake Iznik

ppm	Al	As	Ba	Cd	Co	Cr	Cu	Fe	La	Mn	Ni	Pb	Sr	Zn
Mean	1334	19.7	89.5	0.1	8.9	24.9	19	2317.6	8.4	671.9	23.4	14.3	162.3	44.6
Min.	360	7.9	32.4	0.0	2.7	7.1	7	550.0	3.5	312	5.7	5.0	49	15
Max.	2110	44	272.9	0.3	15.1	53.0	67.7	4000.0	15	1196	51.4	116.6	439.4	89.8
Std. Dev.	493.7	7.8	53.5	0.0	3.3	11.3	11.8	801.8	2.7	245.4	10.8	21.7	120.8	18.1
PEL	-	17	-	3.53	-	90	197	-	-	-	36	91.3	-	315
ERM	-	85	-	9	-	145	390	-	-	-	50	110	-	270
TEL	-	5.9	-	0.6	-	37.3	35.7	-	-	-	18	35	-	123
ERL	-	33	-	5	-	80	70	-	-	-	30	35	-	120
Earth crust	80,000	13	-	0.3	19	90	45	47,200	-	850	68	20	-	95

IRaffinity-1) and a reference polymer library. Polymer identification was achieved through spectral matching based on high similarity between particle spectra and reference library spectra. Thus, even if they matched morphologically, non-plastic particles were eliminated.

A Scanning Electron Microscope (SEM; ZEISS Supra 40 VP) was used to determine the surface morphology and microstructural characteristics of the selected MP samples. The particles were coated with a thin layer of platinum prior to scanning to increase electrical conductivity and improve image quality. After coating, they were placed on carbon adhesive tape and SEM images were obtained at 125×, 500× and 10,000× magnification at an acceleration voltage of 10 kV. Energy Dispersive X-ray Spectroscopy (EDX) was used to determine the Ms types on the MP surfaces.

2.6 Quality assurance and quality control (QA/QC)

To minimize the risk of MP contamination before and during the experiment, a plastic-free protocol was strictly implemented. All procedures (analytical procedures, digestion and filtration processes) were carried out in a safety cabinet using glass and metal equipment. Laboratory coats and disposable latex gloves were worn during laboratory procedures. All glassware and utensils were first washed with detergent, then rinsed three times with 70% ethanol, and finally rinsed with filtered deionized water. Work surfaces were cleaned with 70% ethanol before each work session and throughout the experiment. All solutions, including deionized water used for sample preparation and cleaning, were filtered through 1.6 µm glass fibre filter membranes.

To monitor and measure airborne and procedural contamination, both environmental and procedural blank samples were prepared. To understand airborne contamination, filters were placed in open-top Petri dishes moistened with filtered deionized water inside the biosafety cabinet. Procedural blank samples were analyzed at the end of the experiment by following the protocols applied to sediment samples (without sediment samples). No significant contamination was detected in either case.

The QA/QC measures implemented have ensured the reliability and reproducibility of the MP study, while also enabling the elimination of inter-sample variability and airborne contamination. Furthermore, recovery experiments were not conducted here because the methodology applied has been used in previous studies and has been comprehensively evaluated and validated. The reported recovery efficiency for polymer types has been reported to vary between 60% and 90%, depending on the type of polymer and its morphology (Coppock et al. 2017; Koelmans et al. 2017). For all these reasons, this study focuses on the station-based distribution of Ms and MP accumulation and

the relationship between them, rather than being based on quantity determination.

2.7 Statistical analysis

All the analysis throughout this study was done by using R (version 4.2.3). P-values less than 0.05 considered as a significant threshold. Twenty-five stations from Lake Iznik were examined for 14 Ms. Spearman correlation analysis, principal component analysis (PCA), and hierarchical clustering methods were used to show the covariation patterns and possible source relationships of heavy metal concentrations. Before applying PCA, the data structure was pre-analized for assumptions using the Bartlett test and KMO (Kaiser–Meyer–Olkin) measure to determine whether the differences between variables were suitable for this analysis. These statistical methods were applied to identify common behavioral patterns of metals and the similarity structure between samples. To investigate similarities among stations and heavy metals, cluster analysis (CA) and heatmap visualization were performed using the sediment heavy metal concentration data. Prior to analysis, the data were standardized to remove scale differences among variables. Clustering analysis was then applied. The resulting clustered matrix was visualized as a heatmap, where rows represent sampling stations and columns represent heavy metals, and cell colors indicate relative concentration levels. These analyses were used to identify groups of stations and metals with similar patterns. To provide a direct assessment of the spatial distribution of the obtained heavy metal contamination patterns within the Iznik Lake and whether this distribution clusters statistically significant, Getis–Ord Gi* hotspot analysis (Getis and Ord 1992) was applied using the scores obtained from PCA. This analysis was included in the study to statistically examine where high and low pollution levels are spatially concentrated.

3 Results

The surface water area of Lake İznik is 2,246 km². The lake is approximately 32 km long and 10 km wide, and as a deep lake, it reaches a maximum depth of about 70 m. It is located at an elevation of 85 m above sea level. Toward the summer months, the lake water level decreases, with the lowest water levels observed in autumn (Meşeli 2010). The main inflowing streams to Lake İznik are the Karasu (Karadere) and Solöz (Kocadere) rivers. In addition, the lake receives water from karstic areas and surface runoff. The outflow of the lake is provided by the Karsak Stream, which transports excess water to the Gulf of Gemlik. Karsak Stream represents the only surface outlet of Lake İznik (Kasapoğulları 2022). On the western side of the lake, an embankment was constructed to prevent flooding, increasing the lake's water retention capacity and effectively transforming it into a reservoir (Cindoruk 2006). The lake was designated as a protected area in 1990.

3.1 Metal(loid) analysis

Table 1 presents the descriptive statistics and their comparisons with guideline threshold values. While the concentrations of all Ms except As were below their respective effect guideline values, the mean As concentration (19.7 ppm) exceeded the PEL and TEL values but remained below the ERM and ERL thresholds. Figure 2 shows both the overall levels and spatial variations of Ms in the sediments of Lake İznik.

3.2 Evaluation using the sediment quality index

The reason for calculating sediment quality indices is to compare the current amount of Ms with pre-industrial sediment conditions. These indices provide important outputs for assessing environmental Ms risks, understanding the effects of Ms on ecology, and developing appropriate environmental protection strategies. In this study, the index calculations were performed using the data in Table 2.

The contamination factor (CF) values for Ms, except for As, were calculated to be below 1. This indicates that Ms have low contamination levels at all stations. The CF value for As (1.52) was calculated to be in the range of 1–3. This indicates a moderate accumulation of As in the sediment. This value may not indicate a critical level of contamination. However, it indicates that As is enriched in the lake sediment and that As should be continuously monitored.

Enrichment of Cd, Co, Cr, Cu, Mn, Ni, Pb, and Zn in the sediment was determined using the enrichment factor (EF). As showed the highest enrichment with an EF value of 30.86. The enrichment factor is the degree to which Ms concentrations exceed natural background levels. The enrichment of a metal(oid) indicates that both geogenic and anthropogenic effects may contribute to its accumulation in sediments. Geoaccumulation index (Igeo) value of As (0.01) was also higher than that of other Ms. The total toxic unit (TTU) was calculated as 2.51, indicating a certain toxic potential in the sediment. Proportional toxic unit contributions revealed that As accounted for the largest share of total toxicity (46.25%), identifying it as the primary environmental concern in İznik Lake sediments. This was followed by Ni (25.93%) and Cr (11.04%), which also contributed substantially to the overall toxic risk.

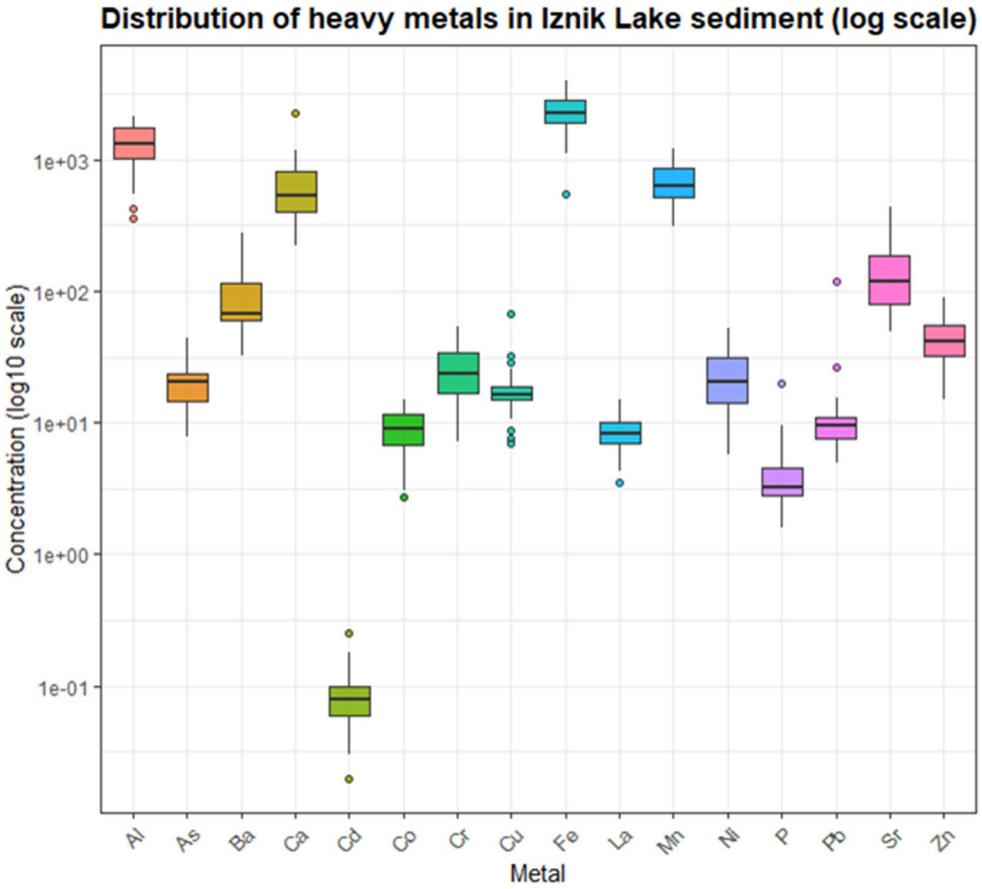


Fig. 2 Distribution of heavy metals in Iznik Lake sediments (log10 scale)

3.3 Microplastic analysis in sediment and EDX results

A total of 247 microplastic particles were identified in the sediments of İznik Lake (Table 3; Fig. 3). The sizes of all detected microplastic particles were measured. The mean size of the microplastics was 1.2 ± 0.9 mm. The largest microplastic particle measured 4.3 mm in length, whereas the smallest particle was 0.21 mm. According to the results of the study, the identified polymer types were styrene–ethylene–butylene–styrene (SEBS), polyacetylene (PAc), polyethylene (PE), high-density polyethylene (HDPE), polyimide (PI), polyacrylamide (PAM), ethylene–vinyl acetate (EVA), and ethylene–acrylic acid (EAA). Selective adsorption behavior assessed by EDX analysis showed that Cu, Zn, Pb, Cd, Cr, and Ni were adsorbed onto MP surfaces, whereas As, Fe, and Mn were not detected (Fig. 4).

3.4 Statistical analyses of Ms accumulated in sediments

In this study, correlation analysis, principal component analysis (PCA), and hierarchical clustering methods were applied to reveal the common behaviors and possible source structures of heavy metal concentrations. These approaches clearly showed that metals were separated into anthropogenic and geogenic groups and that sediment samples clustered according to similar pollution profiles. However, these methods do not directly allow for the statistical evaluation of the geographical distribution of pollution within the Iznik Lake and where it is spatially concentrated. Therefore, Getis–Ord Gi* hotspot analysis was applied using the obtained PCA scores. The Gi* statistic allows for the identification of the actual hotspots and cold spots of human-induced pollution within Iznik Lake with statistical confidence levels by testing whether high and low pollution values cluster spatially significantly. Thus, this analysis provides spatial validation of multivariate statistical findings, revealing not only the presence of pollution but also where it is concentrated and how it spreads. Figure 5 shows a heat map of Spearman correlation coefficients between heavy metals in sediment samples from Lake Iznik. Red and blue colors indicate positive and negative correlations, respectively; color intensity is proportional to the strength of the relationship. The suitability of the dataset for PCA was confirmed by the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity ($p < 0.001$). PCA performed on log-transformed and standardized metal concentrations yielded four components with eigenvalues greater than 1, explaining 84.72% of the total variance (Fig. 6). The PCA

Table 2 Evaluation of metals (metalloids) detected in Iznik Lake sediments based on sediment quality values

Contamination Factor (CF)	Cu	Pb	Zn	Ni	Mn	Fe	As	Co	Cr	Al	Cd
	0.42	0.72	0.47	0.34	0.79	0.05	1.52	0.47	0.28	0.02	0.3
Enrichment Factor (EF)	8.6	14.56	9.57	7.01	16.1	1	30.86	9.53	5.63	0.34	6.11
Geoaccumulation Index (Igeo)	−1.83	−1.07	−1.67	−2.12	−0.92	−4.93	0.01	−1.68	−2.44	−6.49	−2.32
Total Toxic Unit (TTU)					2.51						
Toxic Unit (TU)	0.1	0.16	0.14	0.65			1.16		0.28		0.03
Proportional Toxic Unit (PTU)	3.85	6.25	5.66	25.93			46.25		11.04		1.02

Table 3 Distribution of the microplastic characteristics

Polymer type	*n*	%
Styrene–Ethylene–Butylene–Styrene	99	40.09
Polyacetylene	43	17.41
Polyethylene	37	14.98
High-Density Polyethylene	35	14.17
Polyacrylamide	18	7.29
Polyimide	8	3.24
Ethylene Acrylic Acid	3	1.21
Ethylene–Vinyl Acetate	3	1.21
Other	1	0.40
Total	**247**	**100**
Color	**n**	**%**
Blue	97	39.27
Black	63	25.52
Transparent	46	18.62
Brown	23	9.31
Red	13	5.26
Purple	5	2.02
Total	**247**	**100**
Shape		
Fiber	244	98.8
Fragment	3	1.2

loading matrix (Table 4) and the PCA biplot (Fig. 6) consistently reveal the following information.

According to hierarchical clustering dendrogram (Fig. 7), heavy metals measured in the sediments of Lake Iznik are divided into several main groups according to their co-increase and decrease. That is, some metals are high in the same samples, while others are low together; this points to common sources or shared geochemical behaviors. The main structures have been find in the graph are: Ca – Sr – Ba – As metals cluster together. Pb – Cu – Cd – Zn metals behave together. Cr – Ni pair generally behaves together. Fe – Al – Co – La – Mn metals grouping.

The heat map (Fig. 8) shows z-score standardized heavy metal concentrations. Red and blue colors indicate values above and below the mean for each metal, respectively. This standardization allows for the comparison of metals with different concentration ranges on a common scale and highlights relative enrichment or depletion patterns between sampling stations. The graph shows three main metal blocks: In the first block, Pb – Zn – Cu – Cd – Cr – Ni metals are observed together at high levels, and this group is the anthropogenic pollution group (industrial, agricultural, urban waste). The second block, Fe – Al – Mn La – Co, is the geogenic (natural) group. The third block, Ca – Sr – Ba – As, is the lithological group.

The spatial distribution of anthropogenic pollution in lake sediments was mapped using PC1 values obtained from PCA (Fig. 9a). Additionally, Getis–Ord Gi* analysis was applied to PC1 scores to identify statistically significant hot and cold spots within the lake sediments (Fig. 9b).

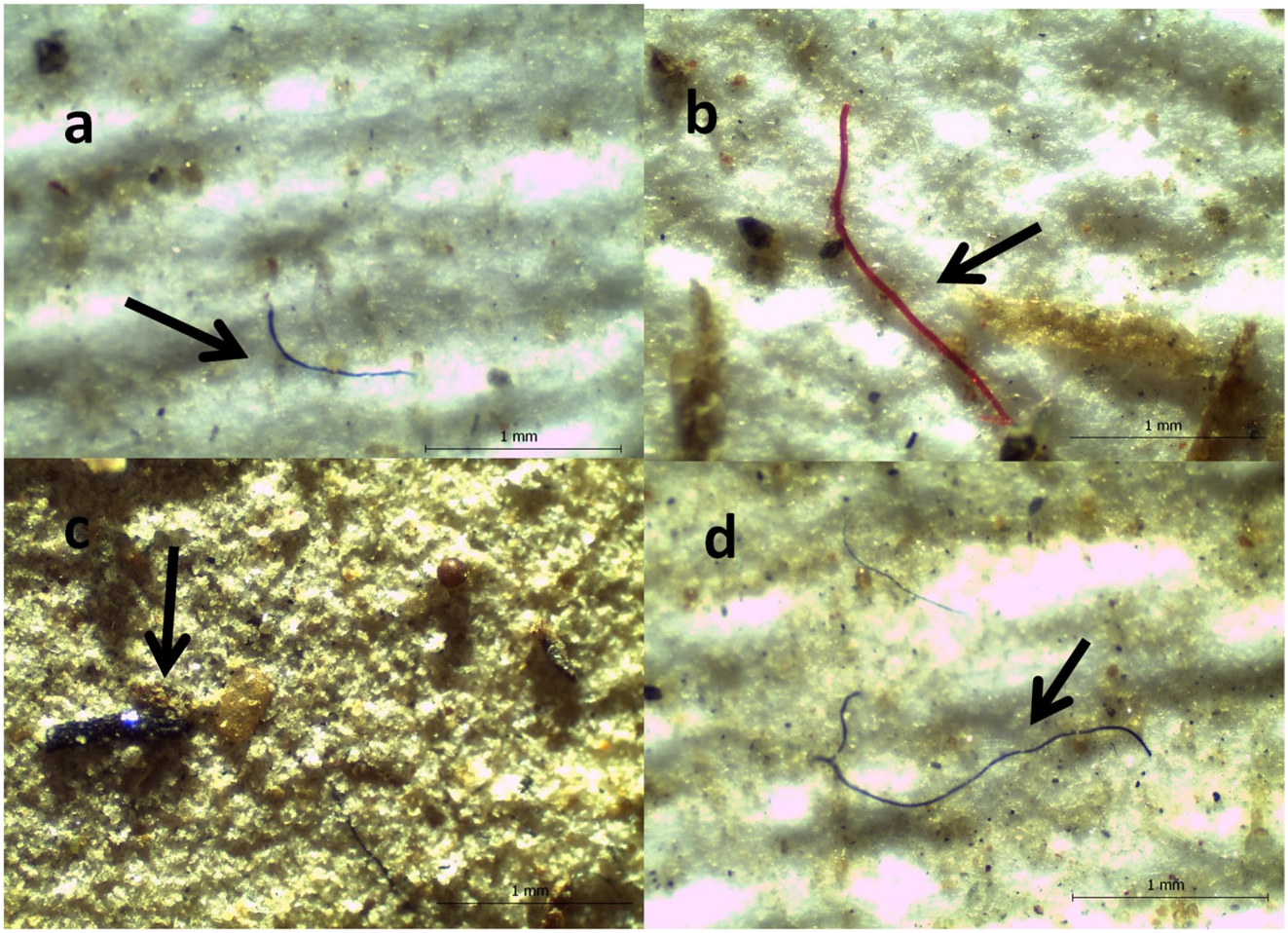


Fig. 3 Images of MPs collected from İznik. **a**, **b**, **c**, **d**: Stereo microscope images a, b,d: fiber, d: fragment

A strong spatial correlation was observed between the two maps. It shows that polluted hot spots correspond to high PC1 values, while clean cold spots correspond to low PC1 values. Station 13 was identified as the most contaminated site in the lake. The elevated pollution levels at this station can be explained by the presence of an organized industrial zone hosting various facilities, including metal-processing industries (pressure vessels, tankers, semi-trailers, evaporators, and cryogenic tank manufacturing plants), pesticide and fertilizer production facilities, a steel factory, livestock farms, and automotive parts manufacturing workshops.

4 Discussion

In this study, it was observed that the accumulation of metals (Ms) in the sediment of Lake Iznik has a multi-component structure rather than a homogeneous one. In principal component analysis (PCA), the strong positive correlation between Al, Co, Fe, La, and Mn in the common component Mn (Al–Co $r = 0.90$***, Fe–Co $r = 0.91$***), indicates that the pathways of entry of these Ms into the sediment are common and that their origins are geogenic. Al, Fe, and Mn are the most abundant Ms in the sediment. This can be attributed to the sediment geochemistry consisting of aluminosilicate minerals and detrital inputs (Li et al. 2003). This finding may also provide a methodological explanation for why Al and Fe are used as reference metals in the indices. The Ms concentrations obtained in the sediment and their behaviour were found to be consistent with natural background data (Turekian and Wedepohl 1961). The co-occurrence of Fe and Mn and their common behaviour may be due to their role as trace elements and carriers (Meriç et al. 2009). Their presence in the first component in PCA and their concentrations below the ERL and TEL values indicate that they are naturally sourced. The relationship between Fe-Mn oxide/hydroxide phases and alumino-silicate minerals is another indication of their natural origin (Yin et al. 2024).

The second principal component of PCA contains Cd, Cu and Zn. Cd, Cu and Zn are separated from As, Fe and Mn found in the first component. This indicates that Cd, Cu and Zn entered the sediment from a different source. The

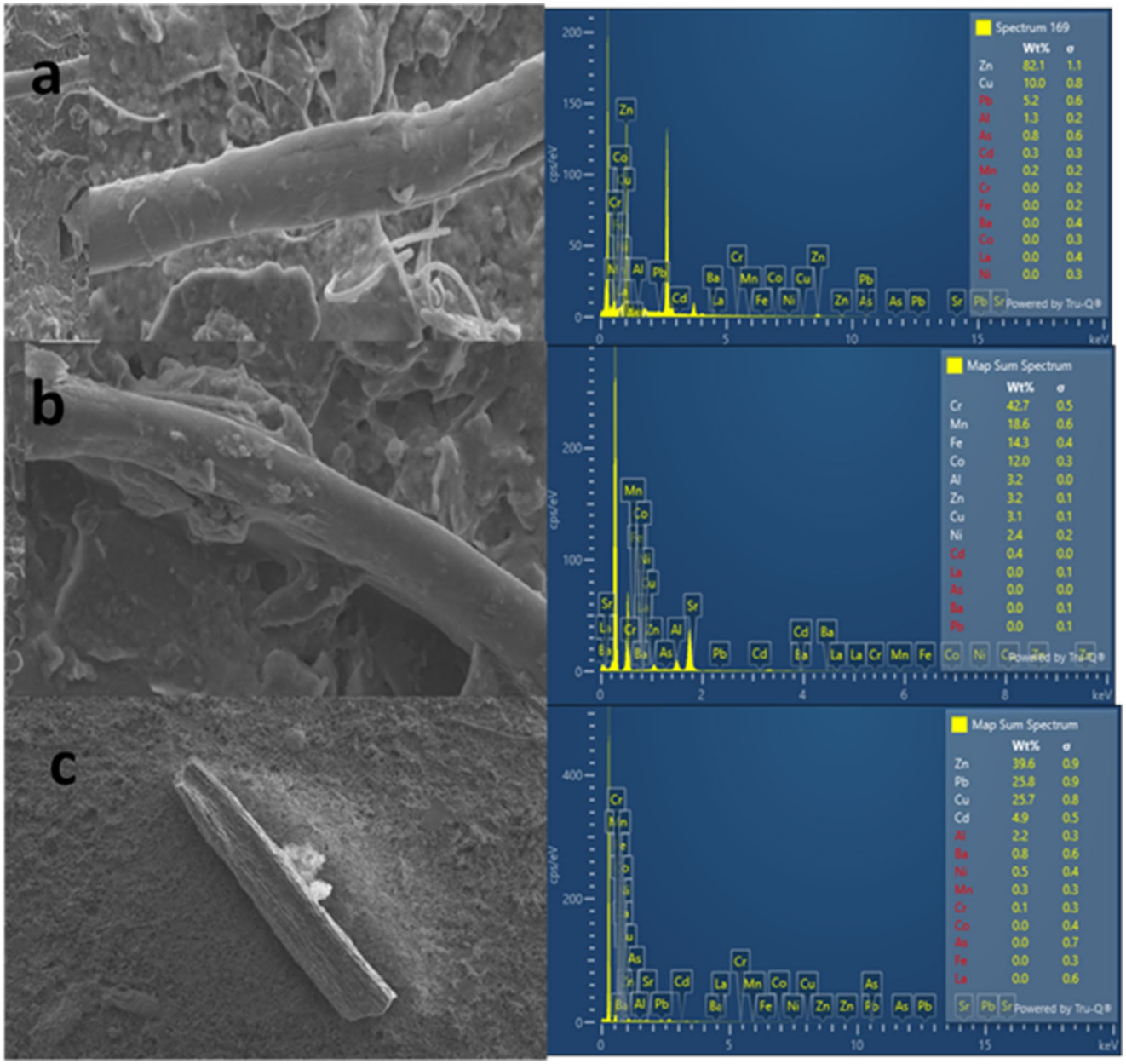


Fig. 4 SEM-EDX analyses of MPs. **a**, **b**: fiber microplastic, **c**: fragment microplastic

presence of Cd, Cu and Zn in the same component indicates that they are controlled by a similar mechanism. The significant positive correlations observed between Cd–Cu, Cd–Zn, and Cu–Zn also indicate that these Ms accumulated together in the lake sediment. The positive correlation between these three Ms and phosphorus (P) may also be due to agricultural inputs. While Cu and Zn in lake sediments may be related to urban waste and agricultural activities, Cd may be related to phosphate fertilisers (Lee et al. 2026). Furthermore, Cd, Cu, and Zn were detected within the ranges defined by sediment quality guideline values (TEL, PEL, ERL, and ERM).

The third principal component of PCA contains Cr, Ni and Pb. These Ms are separated from both the first component, which represents geogenic inputs, and the second component, which is thought to be influenced by agricultural activities. Therefore, it can be said that the third component reflects the effects of different sources. The strong positive correlation between Cr and Ni (r=0.92***) in the same component may indicate that they originate from a common source and/or are subject to similar geochemical processes. The moderate positive correlations between Pb-Cr $(r = 0.43^{*})$ and Pb-Ni $(r = 0.43^{*})$ indicate that

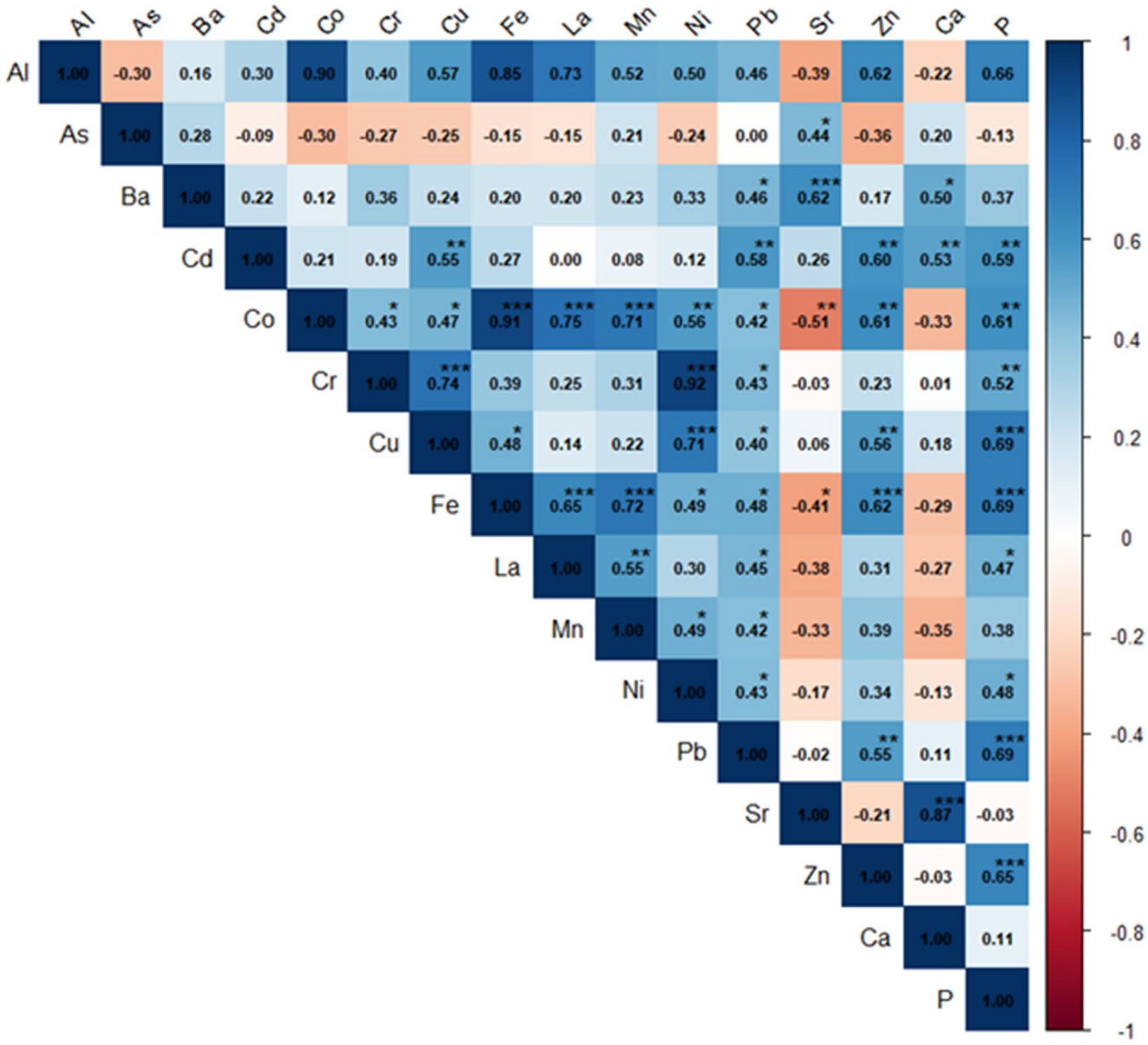


Fig. 5 Heatmap of pairwise correlations among heavy metals in Iznik Lake sediments

Pb accompanies this group as a secondary Ms. This indicates that the accumulation and transport pathways are partially similar. This result is supported by the fact that these three Ms are in the same cluster in the cluster analysis. The co-behavior of Cr and Ni may be associated with sediments derived from serpentinized formations and mafic–ultramafic rocks (Kierczak et al. 2021). In addition, elevated levels of Cr and Ni can also be linked to industrial activities such as stainless-steel production, metal processing, alloy manufacturing, as well as traffic-related emissions (Raffo et al. 2016). The Cr–Ni–Pb group was found to fall within the ERL–ERM and TEL–PEL ranges. Under natural sedimentary conditions, Pb typically exhibits affinity with Al and Fe, particularly Fe/Al oxyhydroxides (Bakshe and Jugade 2024). However, in this study, Pb was grouped with Cr and Ni within the same component, suggesting that a substantial fraction of Pb in the sediments may originate from traffic-related sources and atmospheric deposition (Xie et al. 2026).

The fourth component, which is the final component, contains As, Ba, and Sr together. The sedimentary inputs of Ms in this component also appear to be controlled by a different geochemical process. Ba and Sr, which show accumulation in sediments, are generally associated with carbonate minerals, barite ($BaSO_4$), and Ca-containing phases (Sharma et al. 2025). This situation can also be expressed in terms of regional lithological characteristics. A significant positive correlation was observed between Ba-Sr ($r = 0.62$***). and a strong positive correlation between Sr-Ca

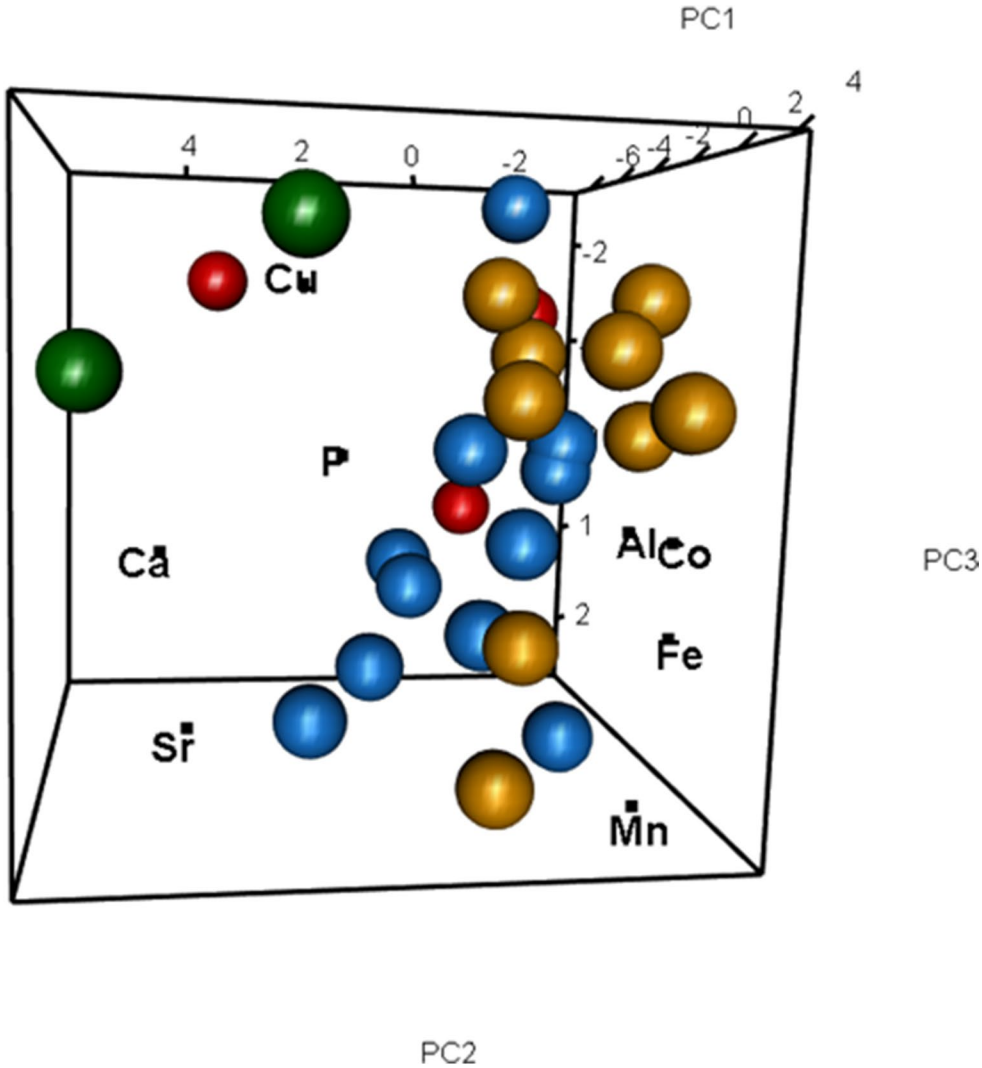


Fig. 6 Three-dimensional PCA plot of the sampling stations. Colors represent the four clusters obtained from k-means clustering based on the PCA scores

Table 4 Factor loadings of heavy metals on the first four PCA

Metal	PC1	PC2	PC3	PC4
Al	0.923	−0.197	0.033	0.164
Co	0.914	−0.308	0.049	0.142
Fe	0.883	−0.319	0.183	0.060
Ni	0.803	−0.055	−0.030	−0.529
P	0.761	0.454	−0.058	0.033
Cr	0.756	0.097	0.011	−0.595
La	0.735	−0.429	0.235	0.081
Zn	0.704	0.300	−0.281	0.466
Mn	0.704	−0.303	0.451	0.212
Cu	0.683	0.546	−0.284	−0.078
Pb	0.598	0.483	−0.137	−0.163
Cd	0.564	0.605	−0.165	0.442
Ba	0.391	0.411	0.607	−0.205
Sr	−0.295	0.787	0.465	−0.050
Ca	−0.281	0.872	0.158	0.055
As	−0.201	−0.009	0.780	0.196

($r = 0.87$***), These relationships indicate that Ba and Sr may be associated with carbonate phases, i.e., they may be explained by a geogenic origin (Kaleem et al. 2021). As is present in the fourth component alongside Ba and Sr. When examining its relationship with Al, Fe, and Mn, no significant correlation was observed. It has been reported that the geochemical behaviour of As in sediments is influenced by early diagenetic processes (Couture et al. 2010). It has also been reported that As in pore water is influenced by sediment depth and organic matter mineralisation processes (Xing et al. 2024; He et al. 2024). If As in sediment is present alongside Fe-Mn oxides in the same environment, these oxides sequester As, preventing its release into the water column (Zeng et al. 2023). However, in this study, As in sediment associated with sulphate and carbonate phases rather than binding to Fe-Mn oxides. This relationship is weak, and they can become mobile again through redox changes and be released into the water (Masuki et al. 2025). Therefore,

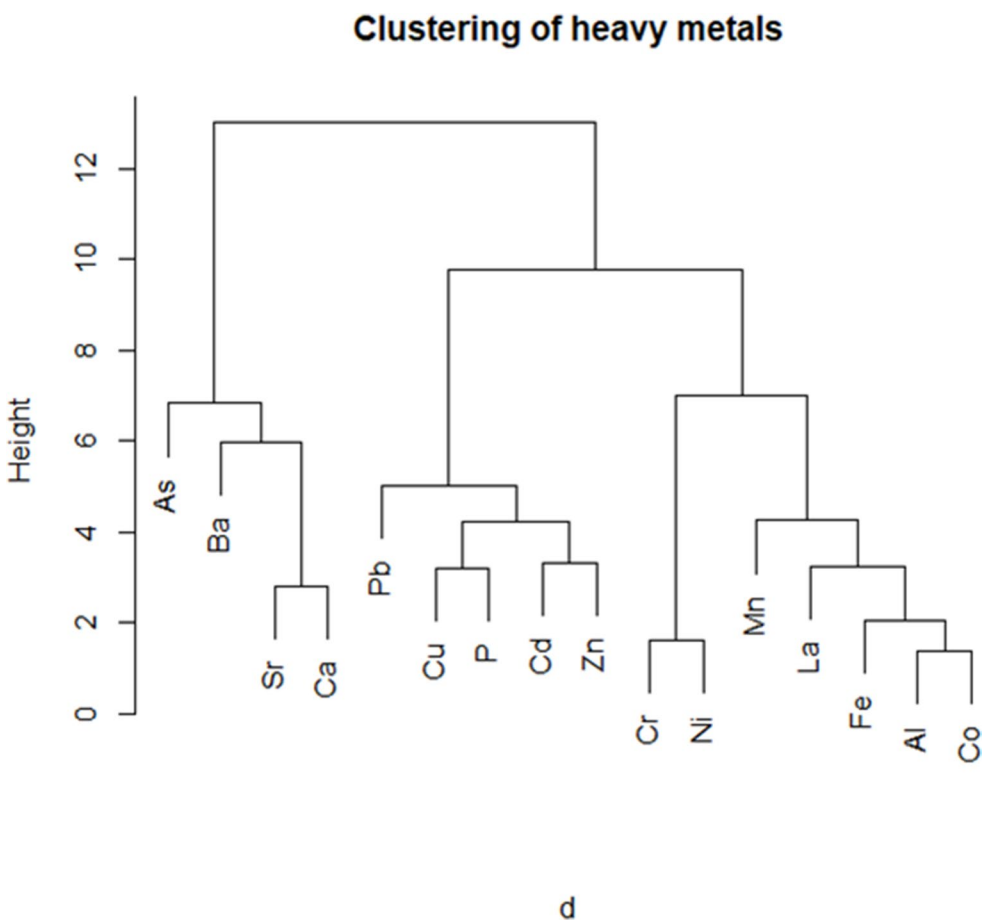


Fig. 7 Hierarchical clustering dendrogram of heavy metals in Iznik Lake sediments

it is thought that the As in the Iznik sediment is in a mobile form sensitive to ion competition.

Although Fe and Mn have the highest concentrations in the sediment, As has been identified as the element posing the greatest toxic risk according to sediment quality indices. As contributes 46.25% to the total toxic unit (ΣTU) and exceeds sediment quality guideline thresholds (ERL–ERM and TEL–PEL). This clearly shows that the toxicity of metals (and metalloids) in sediments cannot be explained solely by their concentration levels. Therefore, the geochemical speciation and environmental behavior of metals (and metalloids) in sediments are clearly important in ecological risk assessments. As can enter wetlands through natural pathways such as volcanic eruptions and weathering of bedrock, and through anthropogenic pathways such as pesticide production, fossil fuel combustion, mining, and smelting industries (Chaudhary 2024). In the general population, exposure to As has been reported to be more effective through ingestion than through inhalation or skin contact (Chung et al. 2014). Therefore, the primary route of exposure to As is primarily through digestion via food intake. Furthermore, As is one of the most toxic compounds found in the environment (ATSDR 2007).

Ms concentrations detected below the ERL threshold rarely have adverse effects on benthic organisms. However, metal(oid) concentrations detected between ERL and ERM values represent a transition zone where toxic effects may occur intermittently, depending on species sensitivity and habitat conditions (Long and Morgan 1991; Abrahim et al. 2008 ;). The detection of As within the ERL-ERM range indicates a low likelihood of acute toxicity. However, the potential for chronic toxicity should not be overlooked, as increased bioavailability associated with remobilisation processes at the sediment-water interface may occur. In such cases, the sediment quality guidelines provide important approaches as a reference when assessing the potential ecological risk posed by a particular sediment type.

The surface chemistry of MP depends on the ionic composition of the sediment, its mineralogical structure, and the type of Ms (Tenea et al. 2024). As a result of the SEM-EDX analysis performed, Cd, Cr, Cu, Ni, Pb, and Zn were detected on the MP surfaces, while As, Fe, and Mn were not detected. As, which shows the highest enrichment in the sediment and contributes most to toxicity, was not adsorbed onto the MP surfaces. This means that the MPs showed selective adsorption for Ms (Chen et al. 2024). This finding indicates not

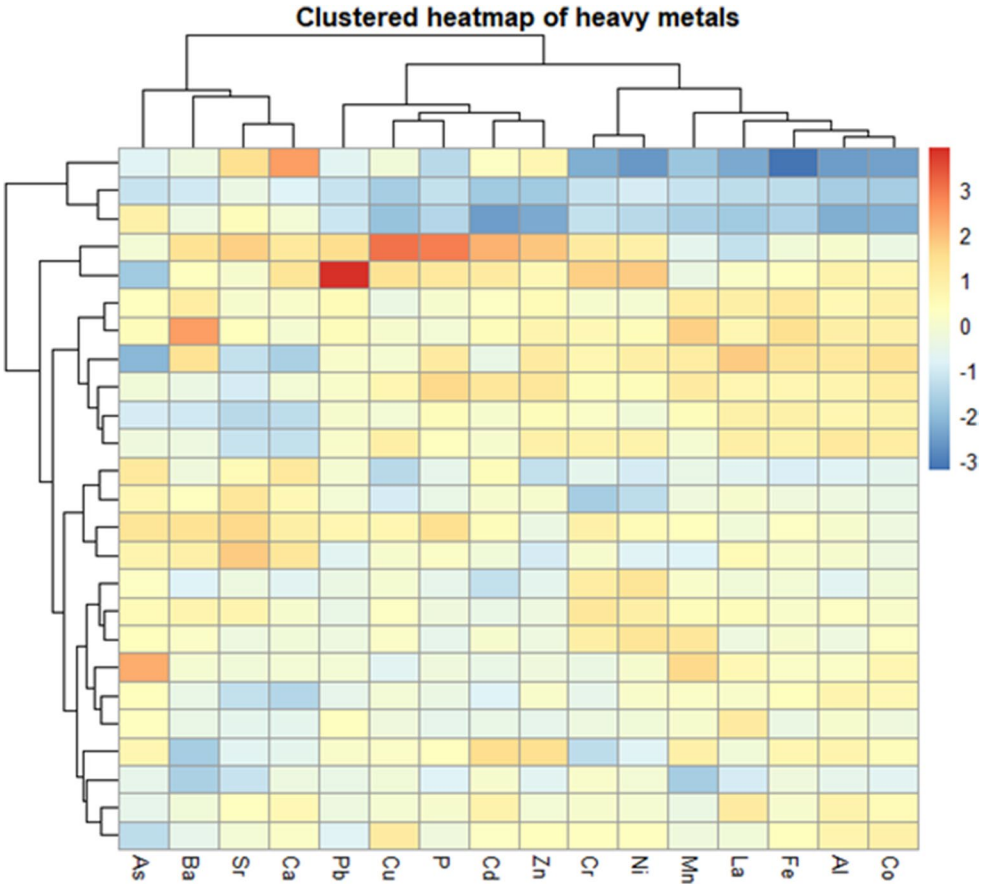


Fig. 8 Hierarchical clustered heatmap of heavy metal concentrations in Iznik Lake sediments. Columns represent heavy metal elements; rows represent the sampling stations no. 1 to 25. The color gradient indicates relative concentration levels, and the dendrograms show clustering patterns among both elements and sampling locations

that the interaction between As and MP is weak, but rather that the type of As in the sediment is incompatible with the surface chemistry of the MP.

Hydrophobic MP surfaces (e.g., polyethylene) favor apolar or weakly polar interactions, whereas As in wetland environments typically occurs as oxyanions—arsenate (As(V) and arsenite (As(III)—such as AsO_4^{3-}, $H_2AsO_4^-$, and AsO_3^{3-}, which are highly polar and strongly hydrated species (Rahman et al. 2024). Microplastics generally exhibit low dielectric constants ($\varepsilon r \approx 2–3$), whereas water has a significantly higher dielectric constant ($\varepsilon r \approx 80$) (Rahman et al. 2024). This strong contrast plays a critical role in ion partitioning between the aqueous phase and microplastic surfaces (Kanduč et al. 2019). As in natural aquatic systems predominantly occurs as oxyanions, as mentioned above, and behaves highly polar and strongly hydrated. This strong hydration causes arsenic species to remain energetically more stable in the high-dielectric aqueous phase.(Mähler et al. 2013; Rahman et al. 2024). In contrast, metal(loid)s that readily adsorb onto MP surfaces are generally present as weakly complexed or cationic species (e.g., Zn^{2+}, Cu^{2+}, Cd^{2+}, Pb^{2+}) (Rasool et al. 2025). During environmental aging, MPs develop oxygen-containing functional groups (–OH, –COOH, C =O) on their surfaces, which can interact with these cations through electrostatic attraction (Huang et al. 2024). In particular, the large specific surface area of fibers MPs provides highly favorable adsorption sites for such metal(loid)s (Murray et al. 2013). The co-occurrence of Zn, Cu, and Cd on MP surfaces is further supported by their grouping in correlation and PCA analyses.

The most prevalent polymer type identified in the sediments was styrene–ethylene–butylene–styrene (SEBS), accounting for 40.2% of the MPs. Styrene–butadiene–styrene (SBS) and styrene–ethylene–butylene–styrene (SEBS) are classified as thermoplastic elastomers belonging to the styrenic block copolymers (TPS; TPE-s) group. SBS consists of two-phase block copolymers with hard and soft segments, where the styrene end blocks impart thermoplastic properties and the butadiene mid-blocks provide elastomeric behavior (Murthe et al. 2022). These materials are widely used in applications where resistance to aging, abrasion, and chemical exposure is not critical, such as adhesives, footwear, agricultural irrigation systems, cable coatings, and seals (Murthe et al. 2022; Crawford et al. 2024). SEBS is formed by the breaking of C=C bonds in the butadiene structure and the emergence of ethylene-butylene middle blocks that provide high mechanical performance, chemical resistance and thermal stability (Murthe et al. 2022). Since SEBS does not occur naturally in nature, its presence in lake sediments can be directly attributed to anthropogenic

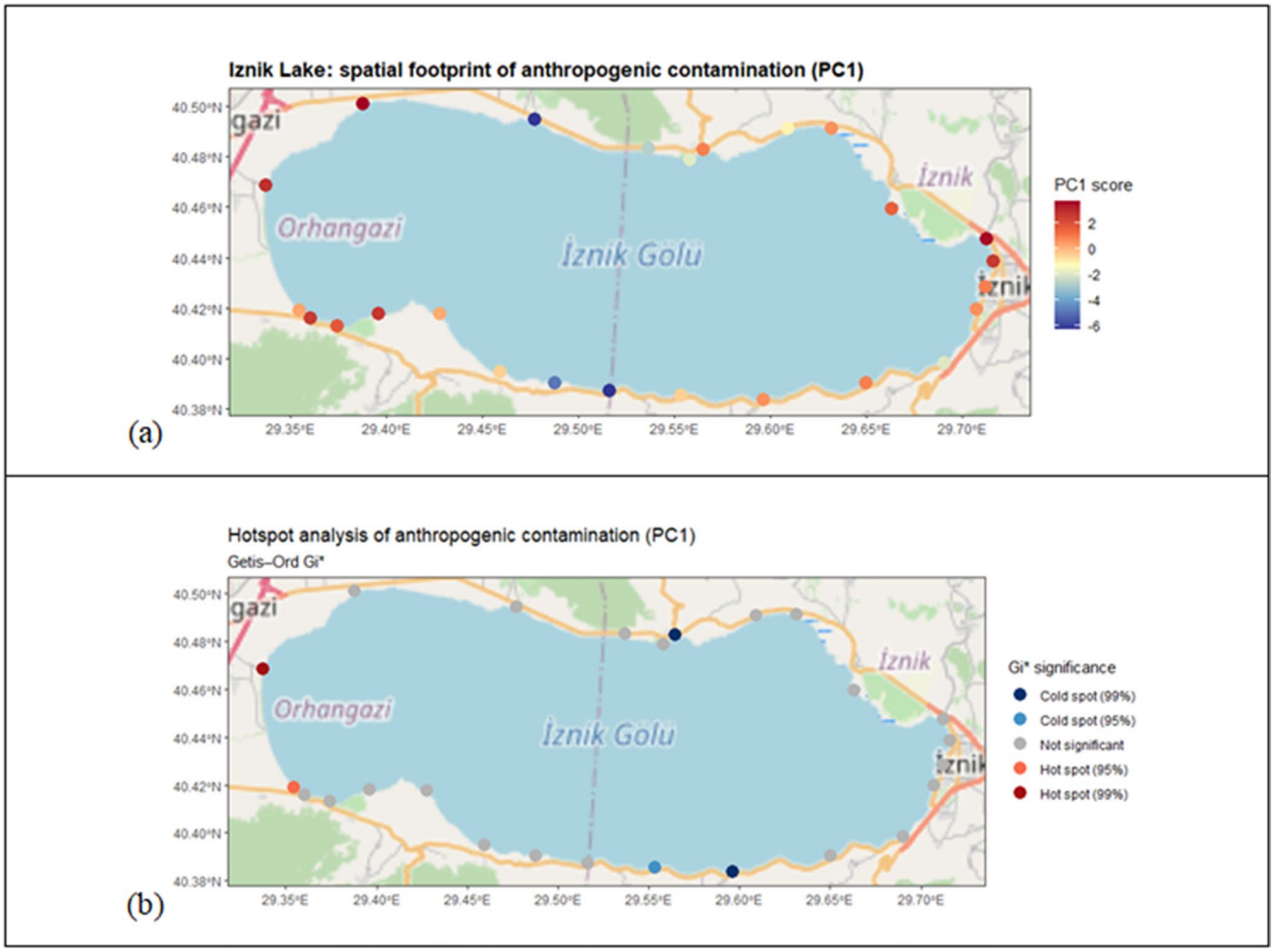


Fig. 9 Spatial footprint (**a**) and Getis–Ord Gi* hotspot analysis (**b**) of PCA-derived anthropogenic contamination (PC1)

input. The accumulation of SEBS in sediments can also be explained by its high density and tendency to aggregate.

The presence of polyacetylene in İznik Lake sediments is also interpreted because of anthropogenic polymer debris. Although polyacetylene is not directly used in plastic manufacturing, it may be associated with highly degraded polymers or abrasion products from electronic materials (Shahid et al. 2025). Because polyacetylene has never been synthesized in an ideal, structurally well-defined form, FTIR-based identification does not necessarily indicate pristine polyacetylene but rather points to conjugated polymeric structures or extensively degraded polymer residues containing extended C =C systems (Hudson 2018). Collectively, these observations suggest that polyacetylene detected in İznik Lake sediments should be regarded as an indicator of advanced polymer aging processes rather than a direct input polymer. Polyethylene can be transported into the lake basin through agricultural activities (e.g., mulching films, greenhouse covers, irrigation pipes), packaging materials such as plastic bags and bottles, and urban drainage systems (Mihai et al. 2021).

The most observed microplastic morphology was fibers. The İznik Lake depression hosts more than 60 settlements, including the district center of Orhangazi as well as smaller towns and villages such as Sölöz, Elbeyli, and Yeniköy. In these settlements, sewage discharges are connected to İznik Lake. Domestic wastewater, microplastics that are not fully removed by wastewater treatment systems, surrounding industrial facilities, and olive-processing plants all contribute to pollution in the lake (Meşeli 2010).

The predominant colors of microplastics detected in sediments are blue and black, although red, brown, transparent, and purple microplastics have also been detected. Polymers containing carbon black are more resistant to UV radiation and mechanical degradation, which allows them to remain in sediments for longer periods (Sarafpour and Pircheraghi 2024). Given that the area around Lake Iznik is open to traffic, the presence of black microplastics may also be related to rubber

wear particles (Reynolds et al. 2024). In contrast, transparent and light-colored microplastics may be less persistent in sediments because they are prone to rapid degradation when exposed to mechanical stress and UV radiation (Li et al. 2024).

5 Conclusion

In this study, the metal(oid) concentrations and microplastic abundances in the sediments of Lake Iznik in northern Turkey were evaluated. The potential contribution of metalloids to toxicity, the origins of their formation, and the morphological characteristics of microplastics (shape, size, and colour) were also assessed. The selective adsorption behaviour of metalloid onto microplastic (MP) surfaces was also examined. Al, Fe, and Mn, found in the first component of principal component analysis (PCA), showed strong positive correlations. This indicates their accumulation in sediments as a result of geogenic processes. Arsenic had the highest relative toxicity ratio and enrichment ratio in lake sediments. Ba and Sr were found in the fourth component. They did not show variability with Fe-Mn oxides but behaved as part of a geochemical process associated with carbonate. SEM-EDX analysis showed that the MP in the lake sediment were not binding phases for As. The relationship between Cd, Cu, and Zn observed in the second major component indicates inputs from domestic wastewater and agricultural activities and subsequent accumulation in sediment. The dominance of blue and black MP in lake sediment suggests that heavy traffic pressure around the lake and agricultural activities may be the main sources of microplastic inputs.

The findings demonstrate that the behavior of microplastics, specifically their ability to selectively adsorb cationic metals while failing to bind with arsenic oxyanions, is governed by chemical speciation and surface-level interactions within the water. This selectivity controls the distribution and potential mobility of metals and metalloids in lake sediments, providing significant data for environmental risk assessments. The results generally emphasize that the mobility and toxicity of MP in Iznik Lake sediments, especially As, should be evaluated in conjunction with sediment geochemical conditions. Therefore, continuous monitoring of the lake is crucial for effective environmental management and risk reduction, and such monitoring studies should explicitly account for sediment geochemical processes.

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Declarations

Conflict of interest The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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