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Tracing microplastic pathways: assessing pollution in a freshwater lake with high tourist activity

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Abstract

Lake Gölçük represents a significant natural freshwater resource within the Gediz River basin, located in the Ödemiş district of İzmir, Türkiye. The ecosystem has experienced considerable anthropogenic pressure from expanding settlements and tourism activities. This study aimed to assess the spatial distribution and severity of microplastic (MP) contamination in the lake. Microplastics (MPs) were quantified and characterized in water, sediment, fish muscle, gastrointestinal tract, and macroinvertebrate tissues collected from three spatially distinct stations using integrated morphological and spectroscopic methods. Macroinvertebrate samples were processed for MP contamination following standardized field sampling and laboratory protocols. The results show that Station 2, corresponding to the primary recreational zone, exhibited the highest MPs concentrations in water (81.33 ± 4.16 particles L^{-1}) and sediment (30.00 ± 4.16 particles kg^{-1}). In macroinvertebrates, MP loads ranged from 0.01 to 0.09 particles mg^{-1} , with peak values observed in Haliplidae and Veliidae taxa. European perch (*Perca fluviatilis*) contained 7.00 ± 2.00 particles g^{-1} in muscle tissue and 1.67 ± 0.58 particles g^{-1} in the gastrointestinal tract, whereas gibel carp (*Carassius gibelio*) from Station 1 showed no detectable MPs. Fibers dominated the morphotype distribution, with blue, black, and transparent particles most prevalent. Polyethylene, polypropylene, polyethylene terephthalate, and nylon constituted the predominant polymer compositions. Collectively, these findings confirm substantial MP contamination across both abiotic (water, sediment) and biotic (fish, macroinvertebrates) compartments of Lake Gölçük, posing potential ecological risks to resident biota and overall ecosystem integrity. The results contribute critical baseline data on MP distribution in Turkish inland waters and underscore the urgent need for protective measures amid escalating tourism pressure.

Keywords Lake Gölçük, Microplastics, Anthropogenic impacts, Freshwater ecosystem, Sustainable habitats

Introduction

Global plastic production, exceeding 400 million tons annually, has led to widespread environmental dispersion of persistent polymeric debris [1]. Microplastics (MPs)—defined as particles < 5 mm—pose significant ecological risks through ingestion, trophic transfer, and potential entry into human food chains [2, 3]. Initially documented in marine systems during the 1970s [4], MPs are now recognized as pervasive contaminants in freshwater environments, entering via surface runoff, wastewater effluents, agricultural discharges, and atmospheric deposition [5, 6].

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Freshwater ecosystems, including lakes and rivers, are particularly vulnerable to anthropogenic stressors, which compromise biodiversity, ecosystem function, and food security [7, 8]. In Türkiye, MPs have been detected in diverse aquatic biota [3, 9], yet systematic, multi-compartment assessments in inland lakes remain scarce.

Lake Gölcük (38.3147°N, 28.0275°E), a high-altitude (1049 m) alluvial lake in the Bozdağ range (Ödemiş, İzmir), serves as a critical headwater of the Gediz River basin and supports rich palustrine and riparian biodiversity [10]. Its accessibility and scenic value drive year-round tourism—particularly nature observation, birdwatching, and water-based recreation—while adjacent agriculture and seasonal irrigation further intensify human impact [11, 12]. These pressures, compounded by habitat degradation and reduced aquatic refugia, threaten ecosystem resilience.

To our knowledge, this study represents the first systematic, multi-compartmental investigation of MP contamination in a Turkish inland lake. Conducted in 2022, it tested targeted hypotheses on spatial heterogeneity and bioaccumulation of MPs across four matrices: surface water, sediment, fish (muscle and gastrointestinal tract), and benthic macroinvertebrates. Particular emphasis was placed on economically and culturally significant fish species consumed locally.

This research aimed to clarify by the following hypotheses: (i) Anthropogenic stressors, particularly tourism and land-use intensification, exert measurable deleterious effects on Lake Gölcük's biodiversity, (ii) MP abundance exhibits significant spatial variation correlated with tourism activity, urban litter inputs, and agricultural runoff, (iii) MPs are present across all sampled compartments (water, sediment, fish, and macroinvertebrates), with evidence of bioaccumulation in consumer-relevant tissues, (iv) Fish muscle tissue in locally consumed species contains MPs, implying potential risks for food security and human health, (v) By establishing a baseline in this high-pressure, data-poor system, the study can inform conservation prioritisation, sustainable tourism planning, and risk assessment in Türkiye's inland waters.

Material and methods

Study area

Lake Gölcük (38.3147°N, 28.0275°E), a small tectonic-alluvial freshwater lake situated in the Bozdağ range of İzmir's Ödemiş district, Türkiye, occupies approximately 0.81 km² within the Gediz River basin [10, 13]. Hydrological recharge is primarily driven by snowmelt and seasonal precipitation during autumn, winter, and spring, whereas summer water levels decline substantially due to irrigation withdrawals [14]. The surrounding marshlands and riparian vegetation sustain high aquatic and

terrestrial biodiversity while facilitating sediment and organic matter retention [10].

Lake Gölcük draws domestic and international visitors year-round for hiking, birdwatching, and water-based recreation, facilitated by its scenic value and accessibility [11]. However, intensifying tourism, agricultural expansion, and recreational fishing are exerting cumulative pressure on the ecosystem. Infrastructure supporting picnic and camping activities sustains visitation across seasons, with peak influxes in spring and summer—when reduced water levels amplify pollution susceptibility [12].

Three sampling stations were established to reflect a gradient of environmental and human disturbance. Station 1 was positioned at the northern inlet adjacent to agricultural land; Station 2 encompassed the central recreational zone under maximal anthropogenic influence; and Station 3 was located at the southern outlet, characterized by minimal disturbance and largely intact littoral vegetation. During peak tourism season, triplicate composite samples of water, sediment, fish, and macroinvertebrates were collected from each station.

Fish, macroinvertebrate sampling and identification

In August 2022, an extensive survey of the health of Lake Gölcük's ecosystem was conducted. The stations varied in depth, substrate composition, and distance from human interference, thereby providing an extensive ecological evaluation. Sampling was performed on both sides of the lake to provide spatial representation of the diversity of fish. Accordingly, fish sampling was carried out at three strategic stations situated in a way to represent various habitat types in the lake during this study (Fig. 1). Three individuals of each species (*Perca fluviatilis*, *Cyprinus carpio*, and *Carassius gibelio*) were collected from each of the three sampling stations (n=9 per species; a total number of fish 27). From each fish, three tissue types, namely muscle, gill, and gastrointestinal tract, were analyzed for their MP content. Each analysis was conducted in triplicate to ensure analytical precision. Individuals analyzed were randomly chosen among the total fish caught at each station.

Fish were sampled using standardized freshwater methods that combined electrofishing along the littoral zone (300–500 V, 50–60 Hz for 15–20 min) and a seine net (with 10-m wings, a 5-m bunt, a total length of 25 m, and a mesh size of 3 mm), depending on the suitability of the sampling area. After catching, fish were euthanized following approved ethical guidelines and preserved in 10% neutral-buffered formaldehyde solution for laboratory examination. Taxonomic classification was determined on the basis of morphology and verified using identification keys [15].

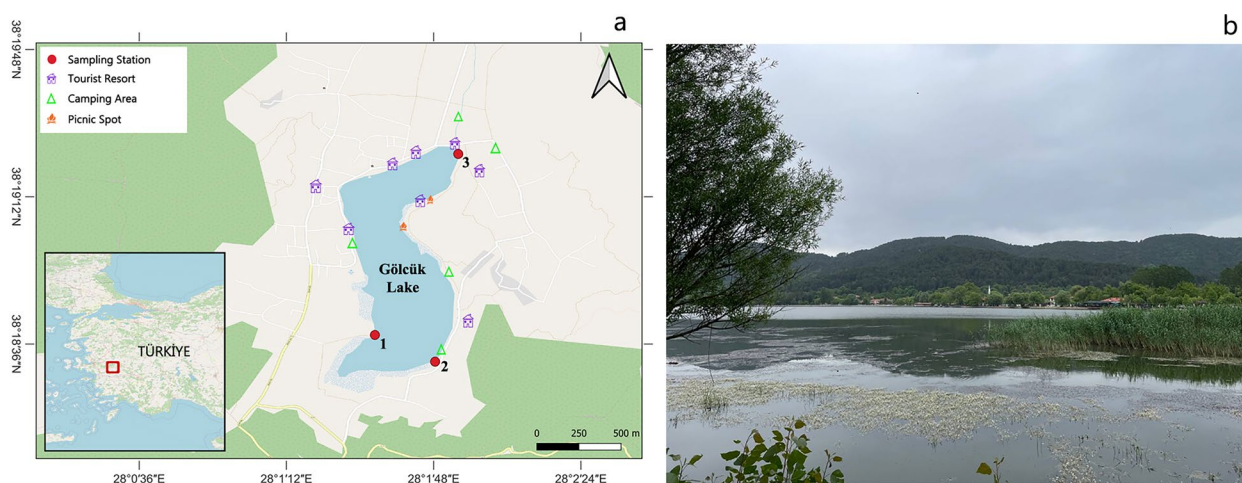


Fig. 1 **a** Study area with the sampling sites, **b** Lake Gölçük

During the sampling period, the surface water temperature was measured as 22.7 °C. Freshwater samples were collected from depths of 20 cm at each sampling station with three replicates collected separately at each sampling location [16]. Samples (1 Liter each) were then placed into a sterile glass sampling jar, to which a 4% formalin solution was added, coated with aluminium foil, sealed, and then stored in a portable refrigerator until arrival at the laboratory.

The sediment samples were sieved through a mesh with a size of 5 mm, and a 300-g aliquot was transferred into a glass jar using a metal spoon, coated with aluminium foil, and sealed.

Littoral macroinvertebrates were collected at each station using a D-frame hand net (mesh 500 µm, frame 25×25 cm) by multi-habitat timed kick-sampling (three 1-min kicks per station) covering representative microhabitats (submerged macrophytes, leaf litter, hard substrates). To include soft-bottom fauna, two Ekman grab samples (225 cm² each) were taken per station in depositional areas and wet-sieved through 500 µm. Taxa were identified primarily to family level and to genus/species when diagnostic characters were preserved; in groups with insufficiently preserved traits (e.g., Haliplidae, Veliidae), a conservative family-level assignment was adopted. Identification followed regional identification keys, and nomenclature was harmonized across stations to ensure comparability.

Extraction of MPs from water, sediment, fish tissues and macroinvertebrates

All the MP experiments were conducted at the MPs Laboratory, Central Research Laboratory Application and Research Center, Ankara Yıldırım Beyazıt

University, Ankara, Türkiye. All sample processing was performed under contamination-controlled conditions. Each matrix had procedural blanks, and all of the reagents were filtered (0.45 µm). During processing, 70% ethanol was used to clean the work surfaces, and aluminium foil was used to cover all containers. Initially, 1 L of freshwater sample was filtered using a vacuum-assisted multi-branch filtration system (Sartorius AG) equipped with GF/F glass fibre filters (47 mm diameter, 0.7 µm pore size). These filters had been treated with 30% H₂O₂ (v/v) to remove organic material [17]. Filters were then dried in glass Petri dishes at 40 °C for 24 h laboratory oven. For sediment analysis, methods from Lots et al. [18] and Besley et al. [19] were followed. Sediment samples were dry sieved through a 5 mm stainless-steel mesh, and 100 g of sediment was dried at 60 °C overnight. Organic matter was digested with 130 mL of 30% H₂O₂ under gentle stirring at room temperature for 24 h. After washing with sterile water and re-drying at 60 °C, a density separation was performed using NaCl solution (1.2 g/cm³; EMSURE®), prepared and used at room temperature (~22–25 °C) with dispersion in an ultrasonic bath for 15 min. The supernatant was subsequently filtered through the same GF/F filtration apparatus, and the filters were oven-dried overnight at 40 °C. Sodium chloride (NaCl; density 1.2 g cm⁻³) was used for density-based separation because it is inexpensive, non-toxic and widely applied in freshwater MP studies.

Gastrointestinal tracts of fish were first dissected, freeze-dried, and homogenized. The samples were digested using 10% potassium hydroxide (KOH) at 60 °C for 72 h following Ng et al. [20], and the digested material was filtered through 0.45 µm glass fibre filters. For muscle tissue, approximately 5 g of fillet per specimen was placed

in glass beakers and similarly digested with 10% KOH under the same conditions. Macroinvertebrate samples were pooled and digested using a hypersaline NaCl solution (1.2 g cm^{-3}) combined with hydrogen peroxide to depigment and dissolve chitin. The resulting suspension was filtered to isolate MPs, which were then oven-dried prior to analysis [21, 22]. Taxonomic identification was conducted primarily to family level using regional dichotomous keys. In instances where diagnostic morphological traits were compromised (e.g., in Haliplidae and Veliidae), specimens were conservatively assigned to family rank to minimize misidentification risk. After MP extraction and filter drying, the isolated particles were classified under a stereomicroscope according to shape (fragment, fibre, film, foam) and colour (transparent, blue, red, etc.).

MP counting, grouping, and characterization

Each particle was visually classified under a stereomicroscope according to shape (fibre, fragment, film, foam), color (transparent, blue, black, red, and others), and size category ($<0.5 \text{ mm}$, $0.5\text{--}1 \text{ mm}$, $1\text{--}3 \text{ mm}$, $3\text{--}5 \text{ mm}$). Surface morphology and size were also further investigated by a Confocal Raman Microscope Spectrometer (JASCO NRS4500) to separate MPs based on the spectral features [23]. To confirm the polymer composition, a representative subsample corresponding to 15% of the total extracted MPs (160 particles; 80 analysed by Raman and 80 by FTIR) was characterized using FTIR, following the protocols recommended by the National Oceanic and Atmospheric Administration (Masura et al., 2015).

Raman analysis

Further to the categorization of MPs under the microscope, the identification of the polymer type was made using laser confocal micro-Raman spectroscopy (NRS-4500 JASCO) with specific wavelengths ranging from 532 to 785 nm (Xi et al. 2019). The diameter of the laser spot was $0.6 \mu\text{m}$, the integration time was 10 s, the resolution of the spectrum was 10 cm^{-1} , and the laser intensity was 0.1%. The specialized software and reference spectrum library of the system decided the kind of MPs.

In total, 80 visually suspected particles (20 from each sample group) were analyzed in all the sampling stations. Of these, 68 (85.0%) matched with the reference library spectra ($\geq 70\%$ similarity index) and were thus confirmed as MPs, while 12 (15.0%) showed weak or noisy spectra and were not polymer-characterized [24, 25].

FTIR analysis

MPs were characterized using Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (ATR-FTIR), which enables rapid and precise polymer

identification through distinct infrared absorbance spectra [26, 27].

ATR-FTIR Spectrometer (Jasco FTIR 6700) equipped with an ATR diamond crystal module in the range from 400 to 4000 cm^{-1} . A total of 64 scans were acquired with a 0.25 cm^{-1} resolution. The collected spectral data were evaluated by comparison with reference spectra recorded from unaltered (pristine) MP particles previously in the laboratory. The area represents the absorbance bands inside the relevant wavenumber ranges was calculated using spectra adjusted to the 1413 cm^{-1} peak. The baseline was established at $y=0$ to reduce any bias in the computation of the carbonyl index (CI). Reflection mode was used for characterization of thick and opaque particles [28, 29].

SEM Analyses

Ten randomly selected MP particles were examined by SEM to characterise surface morphology, following Foo et al. [30]. The MPs were glued to double-adhesive carbon tape and covered by gold for 60 s using a sputter coater (Leica ACE 200, Leica Microsystems GmbH, Wetzlar, Germany) with a thickness of 5–6 nm gold. SEM imaging of MPs was performed with a 0.25 nA electron beam accelerated at 10 keV under a vacuum pressure of 10–3 bar in a field emission scanning electron microscope (FE-SEM, Hitachi Hi-Tech, Ltd., SU5000).

Quality assurance and recovery tests

To minimise contamination, 100% cotton lab coats and nitrile gloves were worn throughout all procedures. Work surfaces and all labware were pre-cleaned with 75% ethanol before use and between specimens to prevent cross-contamination. Procedural blanks using KOH were processed in parallel without tissue. GIT sampling and content analysis were conducted in a laminar-flow cabinet under clean-air conditions. All filters were checked under a microscope prior to use. To monitor airborne contamination, Petri dishes containing dampened filters were placed next to the samples during microscopic examinations and subsequently checked for MPs (procedural blanks). If any particles were detected in blanks, all prior steps were repeated and the affected samples were excluded from the dataset. To evaluate method accuracy, a recovery test was conducted following Tagg et al. [29] and Foo et al. [30]. HDPE ($34\text{--}50 \mu\text{m}$) and polystyrene ($10 \mu\text{m}$) particles were spiked into water, sediment, and biota matrices. For each analysis day, three procedural blanks and three matrix blanks were prepared for each matrix type. To assess recovery performance, 10 particles of each polymer were added to the water, sediment, and biota samples, and all experimental procedures were carried out identically to those applied to the test groups.

For data correction, the mean values obtained from procedural blanks and matrix blanks were subtracted from the total number of detected particles in each sample. Typical recovery efficiencies for comparable freshwater MP protocols range from 85 to 95%, signifying negligible particle loss during preparation.

Statistical analysis

The abundance of MPs in freshwater, sediment, fish muscle and gastrointestinal system of fish was calculated in terms of particles. A one-way analysis of variance (ANOVA) test was performed using IBM SPSS 22.0 software (Chicago, IL, USA) to determine the differences in terms of colour, size, and shape of MPs in all samples from all sampling stations. All statistical analyses were conducted in triplicate from each sample group. When significant differences were detected, Tukey's Honest Significant Difference (HSD) post-hoc test was applied to determine pairwise group differences. Statistical significance was accepted at $p < 0.05$, and all data are presented as mean $\pm$ standard deviation (SD) of triplicate measurements Table 1.

Results

Spatial differences of MPs in macroinvertebrates

MP concentrations in macroinvertebrates ranged from 0.01 to 0.09 MP mg^{-1} . The highest MP loads were recorded in Haliplidae and Veliidae, with 0.08 and 0.09 MP mg^{-1} , respectively. The results clearly showed that the bioaccumulation of MPs in macroinvertebrates also differed spatially, for instance, while 0.08 MP mg^{-1} were determined in Haliplidae from Station 2, the abundance of MPs in the same species was detected as 0.04 MP mg^{-1} .

Spatial differences of MPs in freshwater and sediment

MP concentrations showed clear spatial variability across the three sampling stations. Water samples exhibited the highest MP loads at the second station (81.33 ± 4.16 particles L^{-1}), followed by the third (71.67 ± 4.16 particles L^{-1}) and first station (58.67 ± 8.02 particles L^{-1}). A similar spatial pattern was observed in sediment, where MP levels peaked at the second station (30.00 ± 4.16 particles kg^{-1}) and were lowest at the first station (18.67 ± 3.51 particles kg^{-1}). These patterns indicate that Station 2, which is exposed to the highest anthropogenic pressure, receives greater MP inputs and deposition. The elevated MP levels at Station 3 suggest the presence of persistent input sources, whereas Station 1 exhibited significantly lower concentrations (18.67 ± 3.51 particles kg^{-1} ; $p < 0.05$).

Spatial differences of MPs in fish muscle and gastrointestinal system of fish

MP abundances in the muscle and gastrointestinal tissues of perch, carp, and gibel carp are presented in Table 2. The total length of the examined fish ranged from 3 to 15 cm. Statistically important differences in MP quantity were determined among sampling stations in both muscle and gastrointestinal systems of fish species. MPs were detected in both perch and carp, whereas no MPs were found in gibel carp at Station 1. Across all stations, perch consistently accumulated more MPs than carp and gibel carp. Gastrointestinal MP loads exhibited similar spatial patterns to those observed in muscle tissue. Because perch was the most abundant species in the lake, it was used as the primary representative for spatial comparisons of MP accumulation. Fish tissues reflected parallel spatial trends: European perch (*P. fluviatilis*) showed highest muscle MP loads at the second station (7.00 ± 2.00 particles g^{-1}), followed by the third (4.67 ± 2.31) and first

Table 1 MP counts in macroinvertebrate samples

1st Station			2nd station			3rd Station		
Taxon	N	MPs mg^{-1}	Taxon	N	MPs mg^{-1}	Taxon	N	MPs mg^{-1}
<i>Planorbis</i> sp.	10	0.03 ± 0.01	Aphelocheiridae	5	0.06 ± 0.01	Planorbidae	25	0.01 ± 0.01
Aphelocheiridae	8	0.02 ± 0.00	Hydrobiidae	10	0.07 ± 0.01	Elminthidae	6	0.03 ± 0.01
Chironomidae	4	0.02 ± 0.00	<i>Bythinella</i> sp.	7	0.05 ± 0.01	Elminthidae	8	0.02 ± 0.00
Philopotamidae	3	0.03 ± 0.00	Hebridae	13	0.05 ± 0.01	Aphelocheiridae	4	0.04 ± 0.01
<i>Leuctra</i> (adult)	5	0.03 ± 0.01	Aeshnidae	3	0.08 ± 0.01	Dixidae	11	0.03 ± 0.01
Noteridae	15	0.02 ± 0.00	Thaumaleidae	8	0.04 ± 0.01	Haliplidae	17	0.04 ± 0.01
<i>Cordulia</i> sp.	5	0.02 ± 0.00	Platycnemidae	4	0.05 ± 0.01	<i>Ranatra linearis</i>	1	0.01 ± 0.01
Platycnemidae	1	0.02 ± 0.00	Veliidae	2	0.09 ± 0.01	<i>Radix</i> sp.	20	0.02 ± 0.00
Ephemeroptera	30	0.02 ± 0.00	Haliplidae	8	0.08 ± 0.01	Platycnemidae	2	0.02 ± 0.00
<i>Radix</i> sp.	40	0.01 ± 0.00				Cordulegasteridae	7	0.02 ± 0.00
						Gyrinidae	9	0.02 ± 0.00

Table 2 The number of MPs detected in water, sediment, fish muscle, and gastrointestinal system samples

MP number	1 st station	2nd station	3rd station
Water (particles L ⁻¹)	58.67 ± 8.02 ^a	81.33 ± 4.16 ^c	71.67 ± 4.16 ^b
Sediment (particles kg ⁻¹)	18.67 ± 3.51 ^a	30.00 ± 4.16 ^b	26.33 ± 4.16 ^b
Muscle of European perch (<i>P. fluviatilis</i>) (particles g ⁻¹)	4.00 ± 1.00 ^a	7.00 ± 2.00 ^b	4.67 ± 2.31 ^a
Gastrointestinal system (<i>P. fluviatilis</i>) (particles g ⁻¹)	0.67 ± 0.58 ^a	1.67 ± 0.58 ^b	1.33 ± 0.58 ^b
Muscle of Carp (<i>C. carpio</i>) (particles g ⁻¹)	3.00 ± 1.73 ^a	6.00 ± 1.73 ^b	4.33 ± 1.53 ^{ab}
Gastrointestinal system (<i>C. carpio</i>) (particles g ⁻¹)	0.67 ± 0.58 ^a	1.33 ± 0.58 ^b	1.00 ± 0.00 ^{ab}
Muscle of Gibel carp (<i>C. gibelio</i>) (particles g ⁻¹)	–	2.33 ± 0.58 ^b	1.33 ± 0.58 ^a
Gastrointestinal system (<i>C. gibelio</i>) (particles g ⁻¹)	–	1.33 ± 0.58 ^b	0.67 ± 0.58 ^a

Data are expressed as mean value ± standard deviation of triplicates. Values followed by different letters in the same line indicate significant differences in MP accumulation in water, sediment, fish muscle, and gastrointestinal system samples ($p < 0.05$)

station (4.00 ± 1.00). In *P. fluviatilis*, gastrointestinal MP loads increased from 0.67 ± 0.58 particles g⁻¹ at the first station to 1.67 ± 0.58 particles g⁻¹ at the second station, mirroring the elevated MP levels in adjacent water and sediment. Similarly, *C. carpio* showed higher gastrointestinal MP accumulation at the second station (1.33 ± 0.58 particles g⁻¹) relative to the first station (0.67 ± 0.58 particles g⁻¹), suggesting that feeding behavior and habitat preference may enhance exposure in areas with greater anthropogenic activity. *C. gibelio*, detected only at downstream stations, also demonstrated measurable gastrointestinal burdens (1.33 ± 0.58 and 0.67 ± 0.58 particles g⁻¹), aligning with the polymer distribution observed in the outlet region.

Shape, size and colour differences of MPs

The size distribution of MPs in water, sediment, fish muscle and gastrointestinal system of fish samples were illustrated in Fig. 2A. In water, MPs ranged from 17.61 to 33.52 µm, with size dominance varying spatially: <0.5 mm particles prevailed at Station 1 (33.52%), whereas 3–5 mm and 1–3 mm fractions were most abundant at Station 2 (32.38%) and Station 3 (32.56%), respectively. A similar pattern emerged in sediment, with <0.5 mm MPs dominant at Station 1 (33.93%), 3–5 mm at Station 2 (47.78%), and 1–3 mm at Station 3 (40.51%).

In fish muscle, MPs were generally smaller than in abiotic matrices; <0.5 mm dominated at Station 1, 3–5 mm at Station 2, and 0.5–1 mm at Station 3—potentially reflecting differential exposure to pollution sources. The GIT exhibited the most heterogeneous size profile: 0.5–1 mm predominated at Station 3, <0.5 mm and 0.5–1 mm was co-dominant at Station 1 (50% each), and 3–5 mm was most prevalent at Station 2.

Morphotype distribution (Fig. 2B) also displayed spatial heterogeneity. Films dominated in water at Station 1, whereas fibres prevailed at Stations 2 (40.16%) and 3

(41.40%). Fibres were consistently dominant in sediment and fish muscle across all stations, with peak abundance in muscle at Station 2 (71.43%), followed by Station 1 (58.33%) and Station 3 (42.86%). The GIT showed markedly lower morphotype diversity, likely due to selective retention and digestive processing.

Spatial differences in MP morphotypes across water, sediment, muscle, and GIT samples are shown in Fig. 2B. While most dominant MPs shape was films from freshwater at Station 1, fibre-shaped MPs were detected at the higher rate from stations 2 and 3 with 40.16% and 41.40%, respectively. Fibre-shaped MPs also dominated the sediment and muscle samples across all stations. While fibre-shaped MPs were detected dominantly from fish muscle from all the sampling stations, the abundance of fibre MPs differed significantly spatially, the highest rate of fibre-shaped MPs were detected from the Station 2 (71.43%) than station 1 (58.33%) and Station 3 (42.86%).

Six MP colors were identified (Fig. 2C): transparent, blue, black, yellow, red, and green. In water, transparent MPs dominated at Station 1 (26.14%), blue at Station 2 (27.46%), and black at Station 3 (29.77%). In sediment, blue prevailed at Stations 1 (39.29%) and 3 (30.38%), while transparent MPs were most common at Station 2. Muscle tissue color profiles mirrored environmental trends: transparent/white at Station 1, black at Station 2, and blue at Station 3. GIT color distributions closely aligned with muscle, suggesting trophic consistency. Polymer composition (Fig. 2D) varied spatially: polyethylene (PE) and polypropylene (PP) dominated at Stations 1 and 2, whereas polyethylene terephthalate (PET) and polyamide (nylon) were most abundant at Station 3. Polymer diversity was highest in water, sediment, and muscle, and lowest in the GIT across all sites—indicative of selective bioaccumulation.

These spatially structured variations in MP size, shape, color, and polymer type underscore the influence of localized anthropogenic inputs and highlight differential

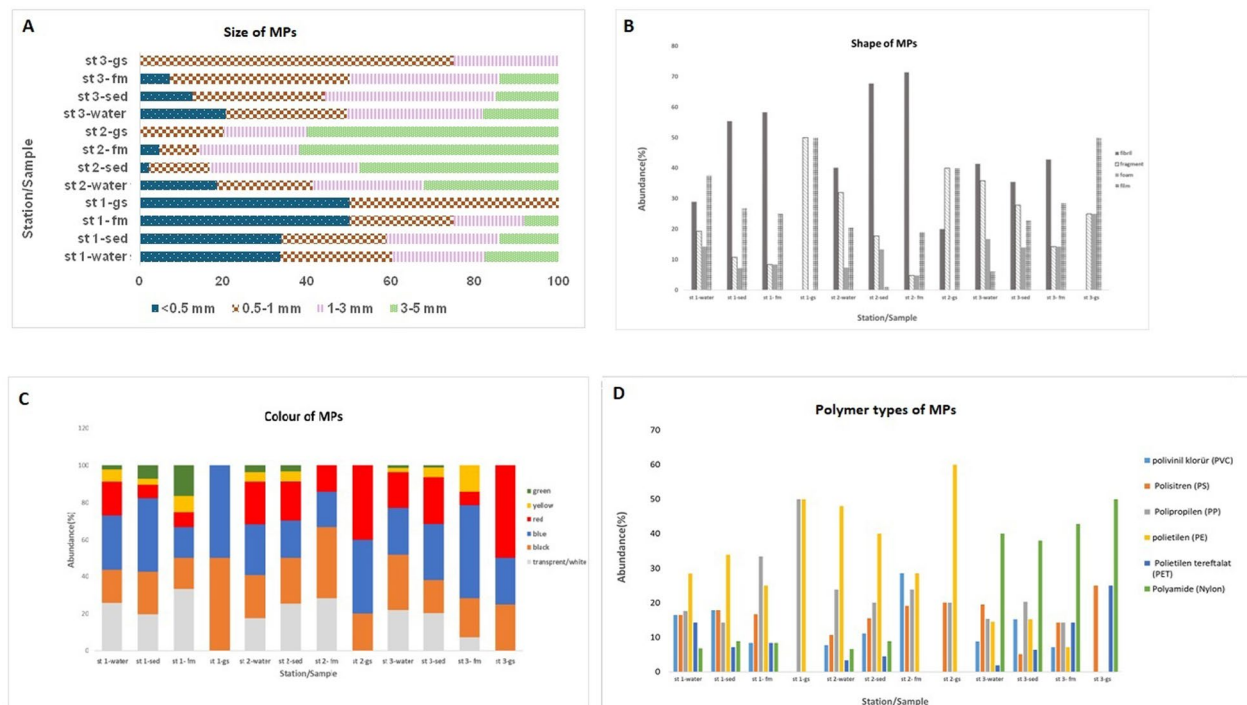


Fig. 2 Classification of MPs. Type of polymer, size, shape and colour distribution of. **A:** Size distribution of MPs, **B:** Shape distribution of MPs, **C:** Colour of MPs, **D:** Polymer type of MPs in water, sediment, fish muscle and gastrointestinal system of fish from each station. (Water: Freshwater; Sed: Sediment, FM: Fish muscle, GS: Gastrointestinal system)

bioaccumulation pathways within the Lake Gölcük food web.

As shown in Fig. 3, microscope images of randomly selected MPs from water, sediment, fish muscle, and

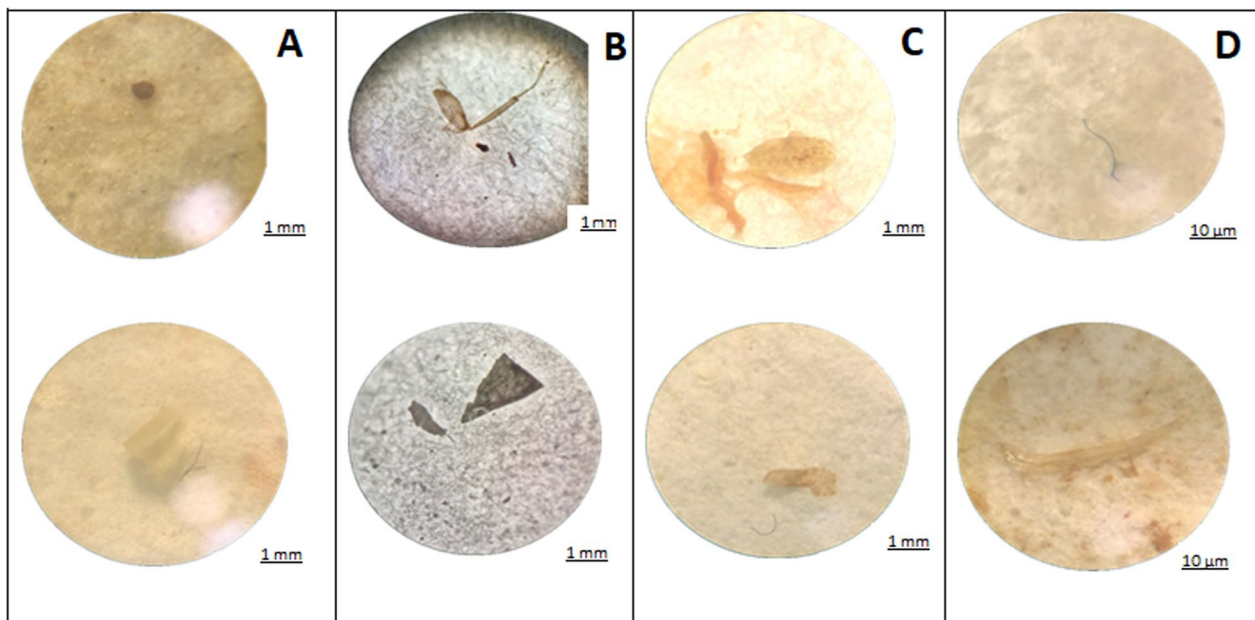


Fig. 3 Microscope images of randomly selected MPs from (A) Bead and fragment from freshwater; (B) Fragments from sediment; (C) Fiber and sheet from fish muscle and (D) Fiber and film from gastrointestinal system of fish

gastrointestinal tract illustrate the diversity of particle shapes and surface textures. The corresponding quantitative results are provided in Table 2. Among the sampling locations, Station 2 exhibited the highest MP loads across all environmental and biological matrices. MP levels at Station 3 were also consistently higher than those observed at Station 1. Overall, each station showed relatively uniform MP deposition within individual sample types, indicating an internally homogeneous distribution pattern.

Polymer characterization of suspected MP particles was performed using Raman and FTIR spectroscopy (Fig. 4). Of the 80 particles subjected to spectral verification, 68 were confirmed as MPs, yielding an identification success rate of 85%. This performance aligns well with Raman–FTIR–based assessments reported for freshwater systems by Rasta et al. [25] and Chiani et al. [24]. The dominant polymer classes detected were polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyamide (Nylon). PE and PP prevailed at Stations 1 and 2, likely reflecting inputs from

tourism-related litter, whereas PET and Nylon were more abundant at Station 3, suggesting contributions from synthetic textiles and fishing activities.

Morphology of MPs

Scanning electron microscopy (SEM) enabled detailed visualization of MP surface morphology, and when integrated with spectroscopic approaches such as FTIR and Raman, it provides a robust framework for characterizing MPs and their associated contaminants in aquatic environments [31]. SEM micrographs of particles randomly selected from water, sediment, fish muscle, and gastrointestinal samples are presented in Fig. 5. The analysis revealed MPs with predominantly spherical or aggregated forms, accompanied by irregular fragments, fractures, and vermiculate structures. High-magnification views showed surface cracks, pits, and cavities, features typically associated with environmental weathering processes and potential interactions with biota or adsorbed pollutants. Additional SEM observations demonstrated abundant biofilm residues,

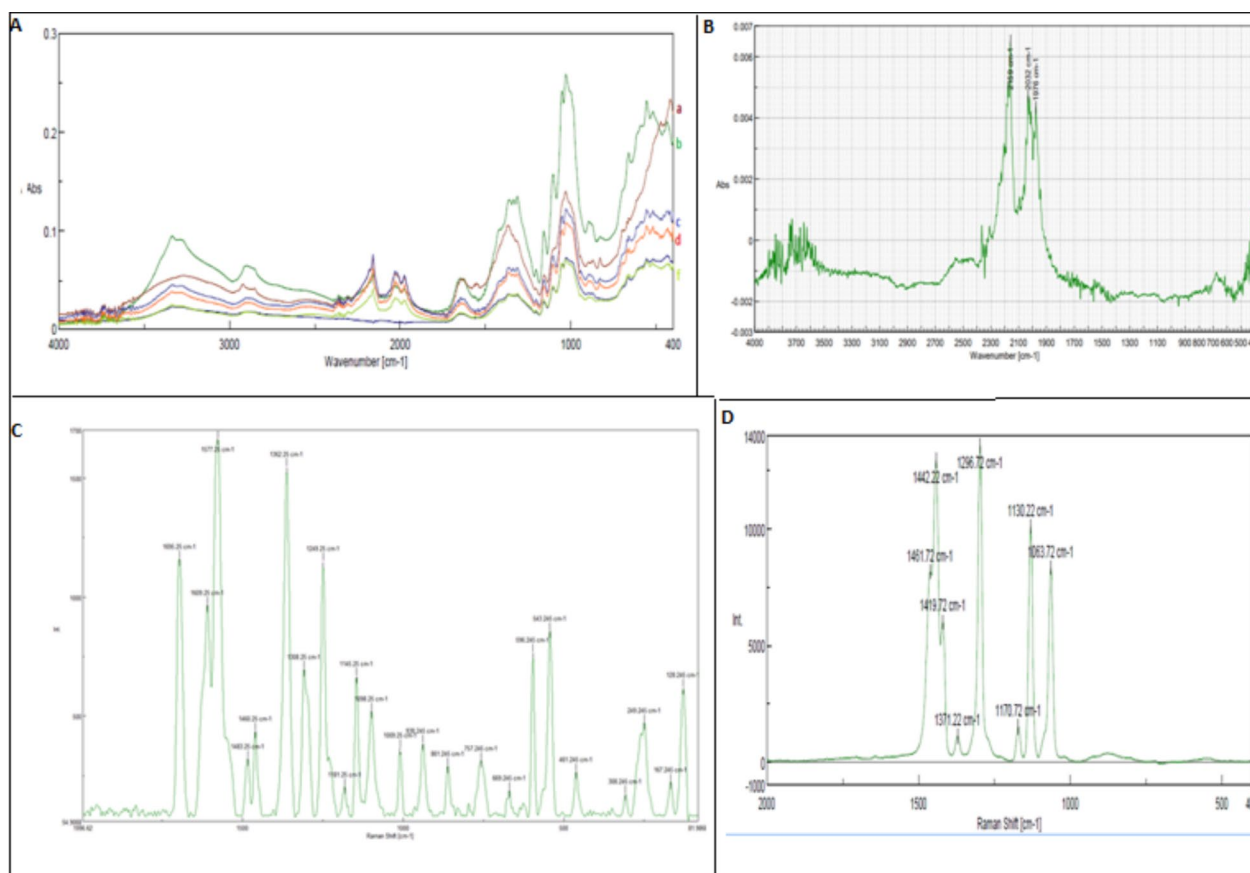


Fig. 4 Representative microscope and spectroscopic images of MPs isolated from (A) water, (B) sediment, (C) fish muscle, and (D) gastrointestinal tissues with polymer identities annotated on panels when confirmed by μ -Raman/ATR-FTIR. The identified polymers include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyamide (Nylon). Scale bars represent 100 μ m

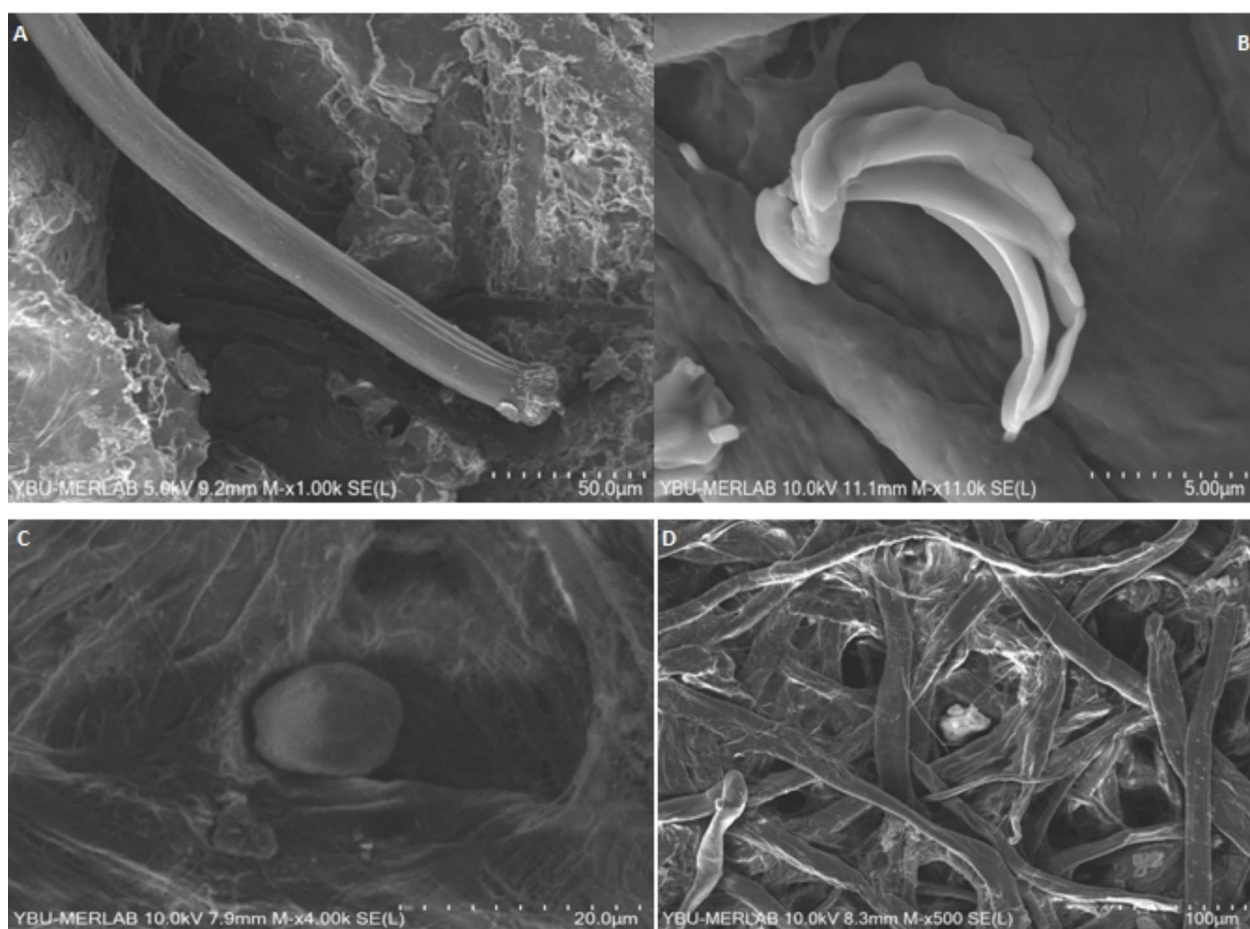


Fig. 5 Micrograph SEM of MPs obtained at different magnifications (**A**) Fibre from freshwater sample, **B** Fragments from gastrointestinal system of fish, **C** Bead and film from (D) Foam and fragments from sediment samples

ruptures, splits, scales, and perforations across MPs derived from freshwater, sediment, and fish tissues. Fibrillar MPs in freshwater samples exhibited porous, fibre-like architectures, whereas foam and fragment-type particles from sediment displayed more complex and heterogeneous surface patterns. As this study reflects a single temporal snapshot of MP accumulation across freshwater compartments, future research incorporating seasonal monitoring under varying environmental stressors would provide a more comprehensive understanding of MP fate and transformation dynamics in freshwater ecosystems. Spectral confirmation using Raman and ATR-FTIR analysis identified polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyamide (Nylon) as the dominant polymer types. PE and PP were primarily associated with stations experiencing intensive tourism pressure, while PET and Nylon were more common at the relatively undisturbed outlet station, consistent with their

expected sources such as packaging materials and textile fibres.

Discussion

The results demonstrate pronounced variation in MP loads among sampling stations in Lake Gölcük, underscoring how local ecological conditions, pollutant inputs, and human activity shape MP distribution and bioaccumulation. The data of MPs bioaccumulation in freshwater and sediment samples align with mounting evidence that freshwater systems act as both conveyors and long-term sinks for MPs; a recent study of several Turkish lakes reported that surface water was dominated by fragment-type MPs while sediments contained mostly fibres, with polyethylene (PE) prevailing in the water column and polypropylene (PP) most abundant in sediments [32]. Globally, MP contamination in sediments shows huge variability from less than one particle per kg to tens of thousands of particles per kg depending

on hydrodynamics, land use, and anthropogenic pressure. In a recent investigation of an urban lake, researchers detected spatial differences in MP concentrations between water and sediment, with mean values of ~29 particles/L in water and ~42 particles/kg in sediment, illustrating that combined monitoring of both compartments better captures overall contamination [33]. Surface alterations observed on MPs are consistent with environmental weathering processes such as photooxidation and UV-induced degradation, which modify polymer integrity and surface chemistry. These weathering effects, combined with polymer-specific structural properties, influence the capacity of MPs to adsorb contaminants including heavy metals and PAHs, corroborating findings from earlier work [31, 34].

MPs abundance differentiation in fish driven by inter-specific and spatial variation. These differences may be influenced by physiological factors such as body size, gut morphology, and integument characteristics [35]. The comparatively higher MP loads observed in perch relative to carp and gibel carp are consistent with species-specific ecological and anatomical traits. Carp and gibel carp possess thicker skin, larger scales, and generally more resilient integuments, potentially affording greater resistance to MP retention or dermal interaction. This interpretation aligns with previous research which demonstrated that MP ingestion in fish is strongly shaped by feeding behavior and morphological attributes [36, 37]. Differences in gastrointestinal MP accumulation may also reflect gut architecture and feeding mode [38], although detailed morphometric analyses were beyond the scope of this study. Perch, with its relatively short gut adapted for rapid digestion of animal prey, likely ingests and retains MPs differently than omnivorous carp species.

Spatial differences in MP abundance and composition reflect heterogeneity in pollution sources, environmental stressors, and hydrodynamic conditions across stations. Particle size is a key parameter for tracking MP sources and understanding their transport through freshwater systems and into the food web. Size variations among MPs recovered from water, sediment, and fish tissues indicate that fragmentation and deposition dynamics are shaped by water quality, seasonal transitions, and local stressors [37, 39]. Similar spatial differences in sediment-associated MPs have been reported by Parker et al. [40] and Kankılıç et al. [41]. Particle size also affects vertical transport processes: larger MPs settle more readily into sediments, influencing their distribution within lake ecosystems [42, 43]. Macroinvertebrates, which are highly responsive to environmental contamination, are widely used as indicators in long-term river health assessments [44, 45], and MPs have been detected in approximately half of riverine macroinvertebrate samples globally [46].

Spatial differences in MP abundance within macroinvertebrates reflect both habitat-specific stressors and species-level feeding strategies [47]. Polymer composition further reflects contrasting pollution regimes across the study area. The predominance of polyethylene (PE) and polypropylene (PP) at Stations 1 and 2 is consistent with recreational activities and mirrors patterns reported in other freshwater systems such as Lake Balaton, Poyang Lake, and Lake Ontario [48–51]. Station 2, which receives intense tourist pressure, showed particularly high PE contributions, similar to trends documented in Lake Victoria [52]. In contrast, the elevated presence of polyethylene terephthalate (PET) and polyamide (Nylon) at Station 3 likely reflects inputs from textile fibres and related anthropogenic activities [53]. These polymer-specific patterns indicate that each station is influenced by distinct pollution sources and environmental processes, including hydrodynamics, industrial effluents, seasonal fluctuations, and tourism-related waste [54]. The dominance of PE and PP may also be linked to common recreational items—such as inflatable toys, fishing lines, buoys—and personal care products used during water-based activities [25, 55–57].

The abundance of MPs also differed depending on environmental matrices; small-sized PE and PP particles dominated the water column, which matched to their frequent presence in fish gastrointestinal tracts, indicating increased bioavailability of low-density polymers that may remain suspended. Larger and denser particles, which are more numerous in sediments, were mirrored in benthic invertebrates that feed on sediments and the additive weight of potential biofilm on MPs. These findings are in accordance with previous research which reported that size and polymer type differentiation between water of and sediment lakes and the polymer variation and vertical redistribution of MPs between matrices were differed by hydrodynamics, density, and settling processes [32, 58]. Differences across fish species were also related to physiological traits: perch, with a shorter and simpler gut, accumulated larger MP loads than carp and gibel carp, which have thicker integument and more complicated digestive morphology, likely decreasing absorption or retention [59]. To evaluate the research hypothesis mentioned in the introduction:

- i) Human activities exert substantial pressure on Lake Gölçük's biodiversity.

The elevated MP concentrations at stations closest to tourist activity -particularly Station 2-strongly support this assumption. Tourism-derived waste appears to be a key contributor to MP inputs, influencing both environmental contamination and bio-

logical accumulation. These results align with the hypothesis that anthropogenic stressors significantly affect ecological integrity. Further biodiversity assessments, including changes in species composition and abundance, would strengthen understanding of MP-related ecological impacts [23, 24].

- ii) MP concentrations are highest where tourism, urban waste, and agricultural runoff converge

MP levels were markedly elevated at Station 2, with a 38.5% higher concentration in water and 1.6 times greater sediment load compared to Station 1. Its proximity to populated tourist areas and potential exposure to urban and agricultural inputs likely amplify contamination. These findings support the hypothesis that multiple anthropogenic sources jointly elevate MP levels. Long-term monitoring, including seasonal sampling, would help confirm the contribution of urban and agricultural runoff.

- iii) MPs occur in all sampled compartments with evidence of bioaccumulation

MPs were detected in water, sediment, macroinvertebrates, and fish tissues, confirming their ubiquity in the lake and their capacity for bioaccumulation. The presence in benthic invertebrates and fish indicates the potential for trophic transfer. Detection in fish muscle is particularly concerning, as it reflects direct entry of MPs into edible tissues.

- iv) Fish muscle tissues contain MPs, posing potential risks to public health

Economically important species such as *C. carpio* and *P. fluviatilis* contained MPs in their muscle tissues, raising potential concerns regarding human exposure. Although toxicological assessment was beyond the scope of this study, future work should address ingestion rates, bioaccumulation pathways, and potential additive and adsorbate toxicity [32, 53, 60]. MP enrichment in gut contents—particularly at Station 2—further emphasizes the role of tourism in driving contamination.

Recent studies have increasingly highlighted the significance of MP pollution in freshwater ecosystems globally. However, the MP monitoring research in freshwater located in Türkiye is limited. For example, Taştan and Sönmez [61] determined the presence of MP abundances in Karaçomak Dam Lake, surface waters and sediments. In another research, Senar and Ulvi, [62] monitored the MPs in Lake Beyşehir. Very recently, Erdoğan [63] analysed MP ingestion benthopelagic fish species from different Turkish lakes and indicated that depth-related exposure pattern and trophic transfer risks impacted bioaccumulation. Due to this research collectively emphasising that Türkiye is a valuable case study region for understanding MP behavior in freshwater bodies, this

current research contributes to this growing body of work by monitoring MP abundance in water, sediment, biota and gastrointestinal systems in a holistic approach.

Given that the analyzed fish species have local economic and dietary importance, the occurrence of MPs in their tissues may pose potential ecological and human health risks. Although quantitative risk assessment was beyond the scope of this study, future research should evaluate ingestion rates, trophic transfer, and potential toxicological impacts to better understand the implications of MP contamination in freshwater food webs. While mechanistic toxicological assessment was beyond our scope, the co-occurrence of MPs in edible tissues highlights potential exposure pathways, warranting targeted risk evaluations (ingestion rates, trophic transfer, and additive/adsorbate toxicity) [27, 56, 60].

Future perspectives

To address escalating MP pollution in Lake Gölcük and comparable freshwater ecosystems, an integrated and interdisciplinary management approach is required. For such ecosystems, an interdisciplinary, multi-faceted management approach is required. The following recommendations from the results clearly highlight;

- a) *Determination of Sources of MPs*: Detailed analysis of the polymer type of MP can identify the industries that are polluting, for example, textile and plastic industries. Identification of the sources will enable targeted waste treatment procedures to be applied to prevent MP release.
- b) *Seasonal and Long-Term Monitoring*: Systematic measurement of MP concentrations, with an emphasis on seasonal changes and long-term trends, will provide valuable data on pollution dynamics. Changes in currents, precipitation, and tourist activity should be considered in order to further clarify MP distribution and persistence.
- c) *Bioaccumulation and Trophic Transfer Studies*: It is necessary to study the bioaccumulation of MPs in aquatic organisms, especially at higher trophic levels. Additionally, the possible risk to human health, more specifically through ingestion of contaminated fish, must be a priority for research. This will be crucial to understand the entirety of MP impacts on human populations.
- d) *Toxicological Studies*: Further ecotoxicological studies are needed to ascertain the fate of MP-associated chemicals such as heavy metal, polycyclic aromatic PAHs, and PCBs on organisms. These studies will clarify the genetic and physiological impact of MPs on aquatic organisms and their long-term influence of toxic chemicals carried by the MP.

- e) *Policy Making and Awareness*: Public awareness needs to be utilized to control MP pollution on the local level. Educational awareness of tourists, locals, and industries about the threat of plastic waste and promoting responsible consumption and disposal of plastics can be utilized to manage the issue of pollution. Better recycling and waste management programs and bans on single-use plastics will be key to ensuring the decimation of MPs from water systems. In the short term, actions such as enhancing public awareness, restricting single-use plastics, and improving recycling infrastructure could help to reduce MP inputs into the lake. Over the medium and long term, adopting sustainable tourism practices, eco-friendly local business models, and consistent environmental monitoring programs will be crucial for protecting freshwater ecosystems such as Lake Gölçük.
- f) *Sustainable Tourism Practices*: Given the strong influence of tourism on MP deposition, the development of sustainable tourism policies is vital. These may include waste-minimization protocols, adoption of environmentally friendly practices by local businesses, and promotion of low-impact recreational activities. Effective implementation will require collaboration among municipal authorities, private enterprises, and civil-society organizations.
- g) *Enhanced Wastewater Treatment and Pollution Control*: Enhancing wastewater treatment facilities and implementing zero-waste practices will reduce the amount of plastic waste released into water bodies. This will, in turn, restrict MP inflows into the lake and other water bodies in the area.

The findings of this study have implications for the necessity to contain MP pollution by a synergy of scientific inquiry, education of the public, and environmental policy reform. Lake Gölçük, as other freshwater environments, is facing growing pressure due to human activities, and the impacts of unregulated pollution are wide ranging. By a joint and active endeavour, it is possible to mitigate the effects of MP pollution and preserve the ecological integrity of this valuable resource for future generations. Constant monitoring of the lake, eco-tourism management, better waste management, and targeted research will be necessary to rescue Lake Gölçük from further decline and secure its long-term ecological health.

Limitations

This study provides a preliminary baseline for MP pollution in Lake Gölçük but is subject to several limitations. For density separation, NaCl at a density of 1.2 g/cm³

may have underestimated high-density polymers, such as PVC and PET. Even with contamination controls, there was still the possibility of the entry of airborne fibres. The present study is a snapshot of one season, August 2022; future research will involve multi-season sampling to capture temporal variability. Future studies should include multi-seasonal samplings, elevated-density flotation media such as NaI and ZnCl₂, and state-of-the-art polymer identification methodologies for more accurate estimates. In addition, despite the use of procedural and airborne blanks, the possibility of contamination by very small airborne fibres cannot be fully excluded, particularly for muscle samples. Our spectroscopic analyses were limited to a representative subsample of visually identified particles, and future studies should aim for higher confirmation rates and finer size resolution (<50 µm) to better assess cellular uptake.

Conclusion

The highest MPs concentrations were recorded across all compartments of Lake Gölçük, especially within the abiotic matrices at the tourism-intensive station and in samples dominated by fibrous particles. The correspondence between polymer composition (PE and PP at heavily impacted sites; PET and PA at the outlet) and organismal burdens suggests that local anthropogenic activities substantially influence both environmental distributions and biological uptake patterns. The detection of MPs in edible fish tissues highlights potential exposure pathways for humans, underscoring the need for targeted risk assessments. As one of the first integrated multi-compartment analyses conducted in a Turkish inland lake, this study establishes a foundational reference for understanding MP dynamics and evaluating the ecological consequences of tourism-related pressures in freshwater systems.

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Author contributions

IK: Conceptualization, investigation, data curation, writing—original draft, supervision, review, and editing. ETAT: Investigation, formal analysis, writing—original draft, review, supervision. CK: Data curation, formal analysis, writing—original draft, review. BB: Writing—original draft, review. HMS: Writing—original draft, supervision.

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Data availability

Data available in article supplementary material.

Declarations

Ethics approval and consent to participate

According to national and institutional regulations in Türkiye, ethical approval is required only for experimental studies involving animals. Based on the decision of the Animal Experiments Ethics Committee of Ege University (dated 11 December 2009, Decision Number 13), and the official letter from the Ministry of Environment and Forestry, General Directorate of Nature Conservation and National Parks (dated 9 April 2010, Reference Number B.18.0.DMP.0.03.05.445.01.01/109/2970), studies that do not include experimental procedures on animals do not require approval from an ethics committee. As this study involved only field sampling and observational data on wild fish populations, and did not include any laboratory experiments or manipulative procedures on live animals, no specific ethics committee approval was required. All procedures, including euthanasia by phenoxyethanol overdose, were carried out by certified researchers under the relevant national permits.

Consent for publication

Not applicable.

Competing interests

The author has no relevant financial or non-financial interests to disclose. The author has no competing interests to declare that are relevant to the content of this article.

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