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Riverine microplastic discharge along the southern Black Sea coast of Türkiye

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Abstract

Rivers are critical pathways of microplastic (MP) pollution to marine environments, yet their contributions to the Black Sea remain understudied. This study evaluates the abundance and characteristics (polymer composition, shape, size, and color) of MPs discharged from 29 rivers flowing into the southern Black Sea. Using a plankton net with a 200 μm mesh size, samples were collected from river mouths, revealing an average MP abundance of 9.63 $\pm$ 1.27 MP m^{-3}, ranging from 1.03 to 29.8 MP m^{-3}. Eastern Black Sea rivers exhibited significantly higher MP levels (11.0 $\pm$ 1.57 MP m^{-3}) compared to western rivers (5.15 $\pm$ 1.25 MP m^{-3}). Annual MP discharge to the Black Sea was estimated at 1.49 $\times$ 10^{11} particles. Polyethylene terephthalate (PET, 59.3% $\pm$ 2.66%), polyethylene (PE, 20.8% $\pm$ 2.04%), and polypropylene (PP, 14.1% $\pm$ 2.36%) were the most common polymers, with PET and PE being significantly dominant. MP sizes ranged predominantly between 200–1000 μm, and fibers constituted the majority of shapes (64.1%), followed by fragments (28.3%). White (36.8% $\pm$ 1.93%) and transparent (30.9% $\pm$ 2.39%) MPs were the most prevalent colors. While no significant differences in MP characteristics were detected between basins (NMDS and ANOSIM), this study emphasizes rivers as major pathways for MP pollution in the Black Sea. These findings underscore the urgent need for targeted mitigation strategies to safeguard marine ecosystems and biodiversity.

1. Introduction

Plastic pollution has become a globally recognized environmental problem [1]. While aquatic environments are the most thoroughly examined, plastic pollution has been documented in diverse settings, including terrestrial regions [2]. Estimates of plastic entering the marine environment from various sources range from 4.8 to 12.7 million [3, 4]. Due to the long lifetime of these pollutants and their continuous entrance into aquatic ecosystems, their concentrations are expected to increase over time, leading to more significant environmental impacts. In aquatic environments, these polymers exist in various size categories, which are mainly classified as macroplastics and microplastics (MPs). A generally accepted definition of MPs is synthetic polymer particles less than 5 mm in size [5]. These particles have been detected in numerous aquatic systems, ranging from oceans to freshwater bodies, including rivers that act as conduits for the transport of land-based plastic waste to the sea [6–8].

Marine organisms, from plankton to marine mammals, are at risk of ingesting MPs, causing digestive blockages, reduced feeding efficiency, and death [9]. MPs also act as vectors for toxic chemicals, such as POPs, heavy metals, and plastic additives, causing chemical toxicity [10, 11]. They disrupt physiological and behavioral functions, impairing growth, reproduction, and predator-prey interactions [12]. MPs bioaccumulate and biomagnify in food chains, impacting apex predators, including humans, with significant health implications due to the global reliance on seafood as a protein source [13, 14].

Recent studies have highlighted the role of rivers in the transport of MPs, demonstrating that they are important pathways for plastics from terrestrial sources to marine environments [15]. Along with directly exporting MPs, rivers also contribute to the fragmentation of macroplastics, which is a significant source of MPs [16, 17]. The transported MPs eventually accumulate in various compartments of the marine environment and aquatic organisms. However, the exact mechanisms governing the transport, distribution, and eventual deposition of MPs in river systems remain poorly understood, especially in the Black Sea, where specific studies are lacking. Depending on the state of the environment and the characteristics of the MPs, they show different transport and accumulation patterns [18–20]. Therefore, *in situ* data collected from different compartments will improve our understanding of the fate of MPs in aquatic environments.

The Black Sea, bordered by countries with varying urbanization and industrialization, is highly vulnerable to MP pollution due to its semi-enclosed nature and significant riverine inputs. While nutrients and metals from rivers have been extensively studied [21–23], models predicting MP transport and hotspots remain unreliable without field validation [15, 24, 25]. Strokal *et al* [24] estimate that rivers from Türkiye will export at least 10% more MPs to the Black Sea by 2050 compared to 2010, with diffuse sources, mainly macroplastic breakdown, driving this trend. Effective management strategies require field-supported studies to address these diffuse sources.

The extent of MP characteristics and export from the river discharge into the Black Sea has yet to be thoroughly quantified [26]. This study aims to address this gap by quantifying the export of MPs from rivers into the Black Sea. The outcomes of this study will contribute to a better understanding of MP pollution in the Black Sea and support the development of targeted strategies to reduce the influx of these contaminants into marine environments.

2. Materials and methods

2.1. Study area

This study was conducted along the southern Black Sea coast of Türkiye, focusing on 29 river mouths discharging into the Black Sea. Sampling was carried out between 19 July and 29 July 2024. The study area covers five major river basins: the Çoruh Basin (station 1), the Eastern Black Sea Basin (EBSB) (stations 2–22), the Yeşilırmak Basin (station 23), the Kızılırmak Basin (station 24), and the Western Black Sea Basin (stations 25–29). The basins vary in size, land use, and hydrological characteristics, contributing to the diverse input of MPs into the Black Sea (figure 1).

Geographically, the southern Black Sea coastline spans both urban and rural settings, with riverine inputs influenced by varying levels of industrial activity, agriculture, and population density. The semi-enclosed nature of the Black Sea makes it particularly vulnerable to pollutant accumulation, as it has limited exchange with the Mediterranean through the Bosphorus Strait. The sampled rivers are critical for assessing the transportation of land-based MPs into the Black Sea. Detailed hydrological characteristics and discharge volumes for each basin are presented in table S1.

2.2. Sampling

During the sampling, all stations were selected close to the river mouths where the flow direction was observed to be toward the sea, ensuring that the collected MPs originated from riverine discharge rather than being influenced by tidal movement from the Black Sea. The samples were collected using plankton nets with a mesh size of 200 μm (20 cm mouth diameter). At each sampling station, three identical nets were deployed simultaneously from a bridge to the river surface and left in place for 10 min. One of these nets was equipped with a mechanical flow meter to quantify the water volume filtered during sampling. After sampling, each net was carefully rinsed with river water, and the collected materials were transferred to glass jars. The jars were then transported to the laboratory and stored at +4 °C until analysis.

2.3. Sample handling and MP extraction

To remove organic substances from the collected three replicate water samples for each station, 50 mL of H_2O_2 was added to each jar, which was then sealed with aluminum foil and incubated at 65 °C for 2–3 d, depending on the organic matter content. After incubation, the samples were vacuum-filtered through Whatman No. 4 filters (20 μm pore size, 47 mm diameter). The filters were subsequently placed in glass petri dishes and stored at room temperature. Multiple filters were used for the water samples with high particle density to enhance reliability and simplify microscopic examination [27, 28].

2.4. Observation and validation of MPs

The filters containing potential MP particles were subjected to microscopic examination (Optika SFX-33). Each particle was manually selected with a needle on a clean filter and then photographed using a digital camera (RoHS A59.4910 cam). Afterward, it was categorized based on shape, size, and color.

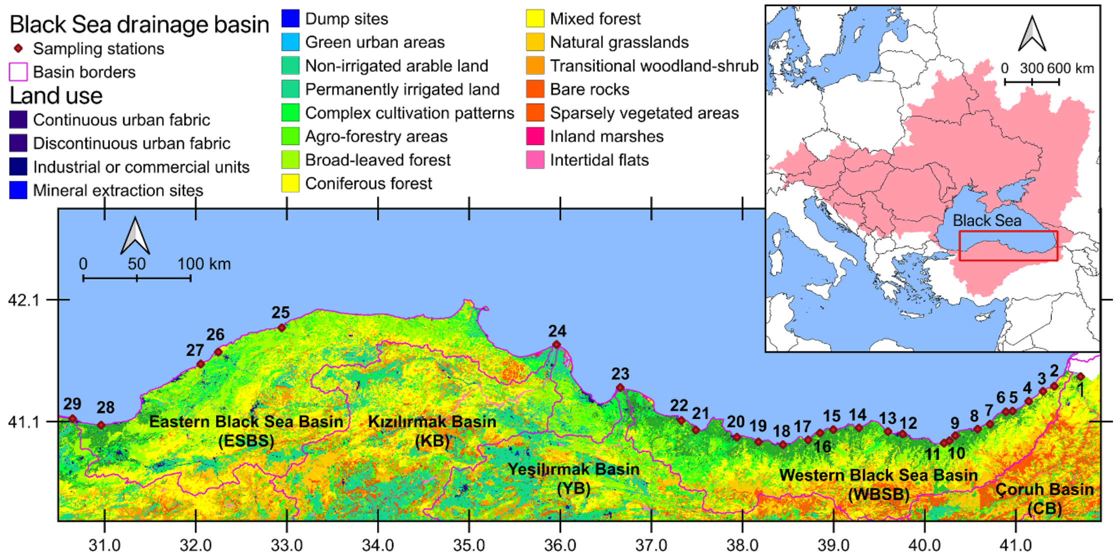

Figure 1. Map showing land use and sampling locations in the study area. (A higher-resolution map with the river system is provided in figure S1).

The particle sizes of the photographed particles were examined using the ImageJ software (http://imagej.nih.gov/ij). Polymer characterization was conducted on 350 representative samples obtained through sub-sampling of the identified particles through sub-sampling. The particles were subjected to analysis using Fourier-transform infrared (FTIR) spectroscopy and a PerkinElmer Spectrum 100 spectrophotometer with an attenuated total reflection (ATR) instrument, with the objective of confirming the presence of polymers. The research was conducted on particles above 100 μm due to the difficulties encountered in correctly locating smaller particles on the ATR crystal and ensuring a precise alignment with the infrared radiation [29]. The spectral wavelength was adjusted to range from 4000 to 650 cm^{-1} in order to identify polymer types, employing 18 repeated scans at a resolution of 4 cm^{-1}. Following the collection of data, a comparison was made with the reference data stored in the instrument's library. Particles with spectra showing a match of more than 70% were identified as MPs (figures 2 and S2).

2.5. Quality control and assurance

A series of rigorous preventive procedures were implemented in the laboratory setting with the objective of ensuring the complete absence of any MP throughout operations. These measures included improvements to the laboratory's airflow enhancements to access points and the implementation of workbench sanitation practices. A designated area was constructed within the laboratory for the purpose of conducting experiments involving MPs. The room is devoid of a ventilation system, including an air conditioning unit. The workbenches were subjected to a rigorous sanitization process, whereby surfaces were delicately wiped with a damp cotton cloth. Moreover, the use of cotton aprons and nitrile gloves was of paramount importance during these procedures. The inclusion of blanks in conjunction with unidentified samples was crucial for guaranteeing quality assurance in MP research [30]. Ten beakers containing only distilled water were used, following the same procedure as that used for the standard samples. Moreover, the potential presence of airborne MP contamination was identified during the microscopic examination of the petri dish. The total quantity of MP was found to be 0.30 $\pm$ 0.48 item filter-1 in the negative blank samples. Moreover, the recovery rate during digestion was determined by employing a collection of positive control samples ($N = 3$). The pre-prepared PET, PE, and PP particles (with a size range of 150–212 μm) were obtained from ground granules [31]. The prepared particles were added to 100 ml of filtered, purified water. The subsequent stages were conducted in accordance with the procedures specified for the standard samples. The stereo microscope was employed to examine the particles that had accumulated on the filter, and the recovery was calculated by dividing the quantity between the initial addition and the consequential amount [29].

2.6. Data analysis

The data were subjected to a Shapiro–Wilk test to ascertain whether they exhibited a normal distribution. Once it had been established that the abundance of MPs data was normally distributed, an independent t-test was employed for the purpose of comparing the abundance, as mentioned above, between the basins in question. The percentage data for MP

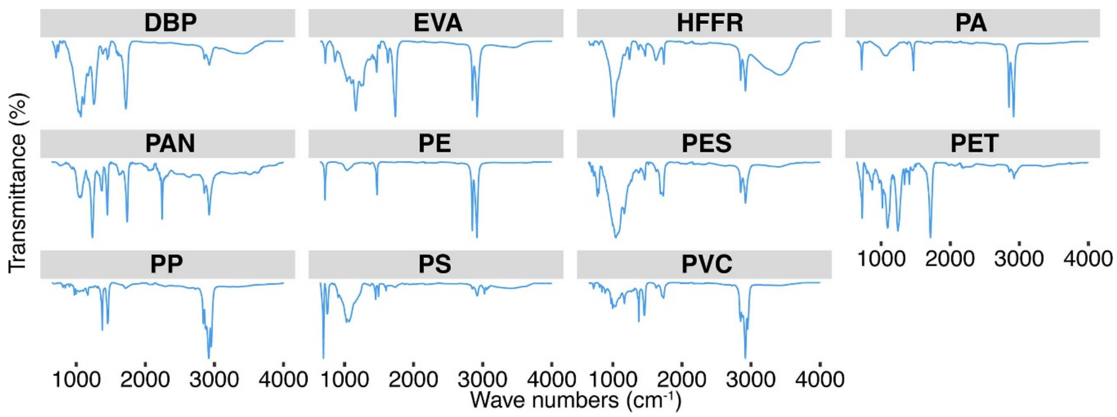

Figure 2. FTIR spectrums of MPs. polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyamide (PA), polyacrylonitrile (PAN), Ethylene-vinyl acetate (EVA), Halogen-free flame retardant (HFFR), polystyrene (PS), Dibutyl phthalate (DBP), polyvinyl chloride (PVC), and polyethersulfone (PES).

characteristics (polymer type, shape, size, and color) did not satisfy the normal distribution criteria; therefore, the Kruskal–Wallis test was used to assess the differences among the characteristics. Subsequently, a Dunn's test was conducted to ascertain which groups exhibited significant differences. The dissimilarities in the characteristic composition among the basins were visualized using non-metric multidimensional scaling (NMDS) and tested using analysis of similarity (ANOSIM). Spearman rank correlation was conducted to determine the correlation between MP abundance and population and flow rates. The data analysis and visualization were conducted using R (ver. 4.4.1). The Shapiro–Wilk test, independent samples *t*-test, Kruskal–Wallis test, and Dunn's test were performed using the rstatix (ver. 0.7.2) package. NMDS and ANOSIM were conducted using the vegan (ver. 2.6–6.1) package. The data were visualized using the ggplot2 package. The data were expressed as mean $\pm$ standard error of the mean. The confidence interval for the statistical tests was set to 95%.

3. Results

A total of 1697 MP were extracted from the collected water samples. The overall abundance varied between 1.03 and 29.8 MP m^{-3} with an average of 9.63 $\pm$ 1.27 MP m^{-3}. The highest abundance was estimated at stations 12 (29.8 MP m^{-3}), 3 (19.2 MP m^{-3}), and 13 (18.8 MP m^{-3}) located in the EBSB, while the lowest abundance was found at stations 29 (1.03 MP m^{-3}), 19 (1.76 MP m^{-3}), and 18 (1.92 MP m^{-3}) (figure 3(A)). A comparison in the average MP abundance between the EBSB (11.0 $\pm$ 1.57 MP m^{-3}) and Western Black Sea Basin (5.15 $\pm$ 1.25 MP m^{-3}) revealed a statistically significant difference (*t*-test, $p < 0.05$) (figure 3(B)). The MP abundance did not show a significant correlation with population ($R^2 = 0.2, p > 0.05$), however, a weak correlation with flow rate ($R^2 = -0.37, p < 0.05$) was determined.

Regarding polymer composition, eleven different types of MPs were identified. Among these, polyethylene terephthalate (PET) was the most prevalent across nearly all stations, excluding station 24, where other polymers were more dominant. PET abundance ranged from 33.3% to 84.6%, with an average of 59.3% $\pm$ 2.66%, significantly exceeding other polymers (Dunn's test, $p < 0.05$). Other common polymers included polyethylene (PE) at 20.8% $\pm$ 2.04%, polypropylene (PP) at 14.1% $\pm$ 2.36%, and polyamide (PA) at 8.51% $\pm$ 2.84% (figure 4(B)). These were more abundant compared to other polymers, with PET consistently more prominent. A NMDS analysis, supported by ANOSIM, indicated no significant difference in polymer composition between the Eastern and Western Basins (figure 4(C)).

MPs were categorized into four shapes, with fibers being the most prevalent, detected across all stations (figure 5(A)). Fiber abundance averaged 64.1% $\pm$ 2.62%, ranging between 33.3% and 86.5%, significantly higher than other shapes (Dunn's test, $p < 0.05$). The second most common shape was fragments, comprising 28.3% $\pm$ 2.33%, followed by films (9.48% $\pm$ 1.32%) and spheres (2.65% $\pm$ 0.86%) (figure 5(B)). The shape composition was consistent across regions, showing overlap in NMDS analysis (ANOSIM, $p > 0.05$, figure 5(C)).

MPs were further analyzed by size class, with results illustrated in figure 6(A). On average, the most common size class was 100–1000 μm, accounting for 41.3% $\pm$ 5.49% of particles, followed by the 4000–5000 μm (23.5% $\pm$ 4.48%) and 3000–4000 μm (22.7% $\pm$ 2.81%) classes. The 100–1000 μm class was significantly more abundant than both the 2000–3000 μm and 4000–5000 μm classes (Dunn's test,

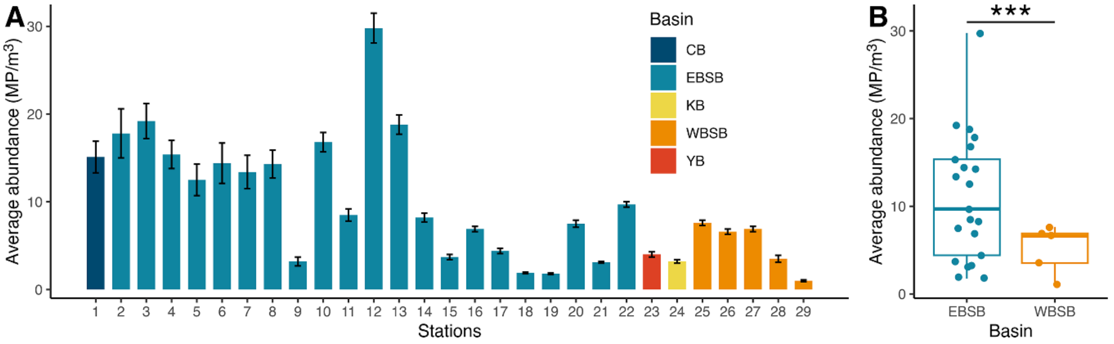

Figure 3. Average abundance of MP by station (A). Comparison between Eastern Black Sea Basin (EBSB) and Western Black Sea Basin (WBSB) (*** indicates statistically significant difference between the groups determined by t-test $p < 0.01$).

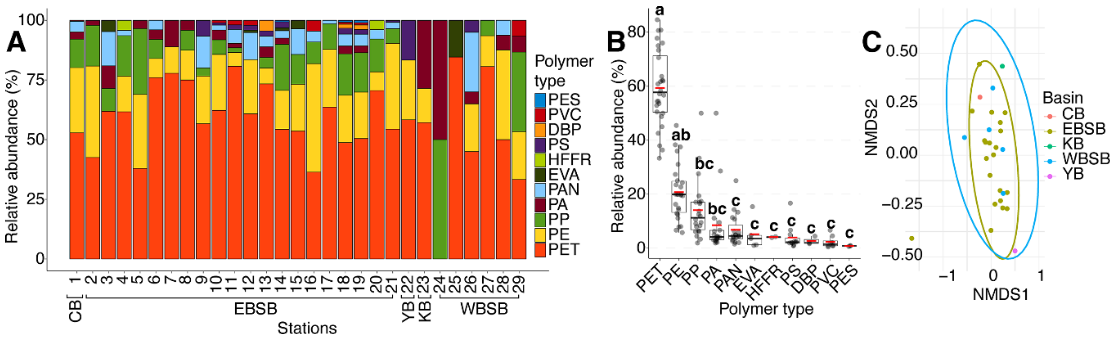

Figure 4. Polymer composition by station (A). Distribution and comparison of relative polymer abundance, with different letters indicating significant differences, determined by Dunn's test (B). NMDS plot illustrating the comparison of polymer composition across basins (CB: Çoruh Basin, EBSB: Eastern Black Sea Basin, KB: Kızılırmak Basin, WBSB: Western Black Sea Basin, YB: Yeşilırmak Basin) (C).

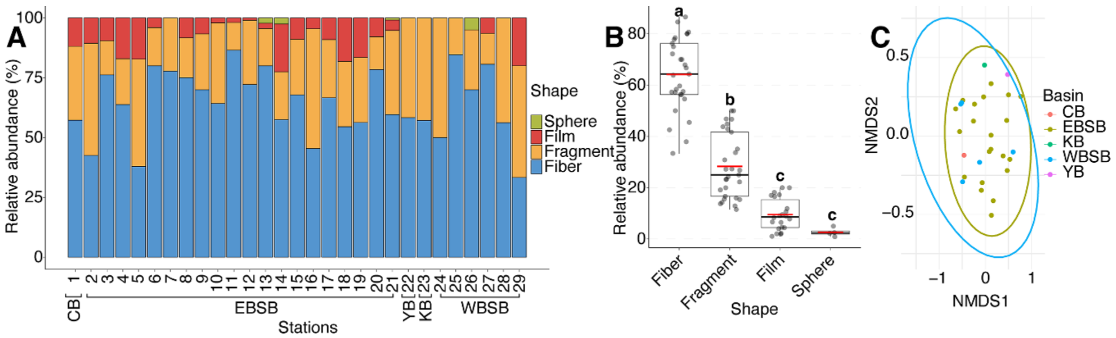

Figure 5. Shape composition by station (A). Distribution and comparison of relative abundance of shapes, with different letters indicating significant differences, determined by Dunn's test (B). NMDS plot illustrating the shape composition comparison across basins (CB: Çoruh Basin, EBSB: Eastern Black Sea Basin, KB: Kızılırmak Basin, WBSB: Western Black Sea Basin, YB: Yeşilırmak Basin) (C).

$p < 0.05$, figure 6(B)). MP sizes varied from 101 to 4997 μm, with an overall average of 2148.3 $\pm$ 37.0 μm (figure 6(C)). Size distribution was also uniform across basins, with average sizes per basin as follows: 4499.6 $\pm$ 111.6 μm in Yeşilırmak Basin, 2198.1 $\pm$ 41.4 μm in the EBSB, 1937.1 $\pm$ 97.2 μm in Çoruh Basin, 1835.7 $\pm$ 147.4 μm in the Western Black Sea Basin, and 916.0 $\pm$ 56.0 μm in Kızılırmak Basin. This distribution is shown in figure 6(d), which also includes NMDS analysis across basins, demonstrating a consistent shape composition (CB: Çoruh Basin, EBSB: EBSB, KB: Kızılırmak Basin, WBSB: Western Black Sea Basin, YB: Yeşilırmak Basin).

A total of eleven different colors were identified in the samples, with white and transparent particles observed at all stations except station 24. These two colors were the most common, making up 22.7% to 65.6% and 10.6% to 54.8% of MPs, respectively (figure 7(A)). The average abundances of white (36.8% $\pm$ 1.93%) and transparent (30.9% $\pm$ 2.39%) MPs were similar and significantly higher than those of the other colors (Dunn's test, $p < 0.05$, figure 7(B)).

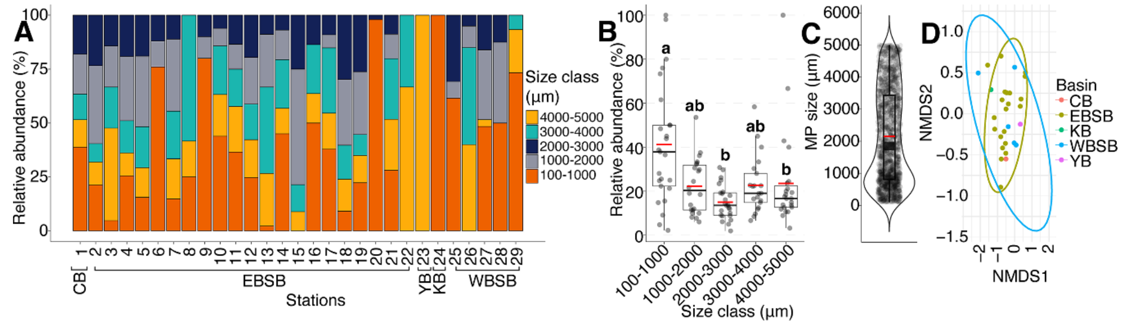

Figure 6. Size class composition by station (A). Distribution and comparison of relative abundance of shapes, with different letters indicating significant differences, determined by Dunn's test (B). Overall size distribution of MP particles (C). NMDS plot illustrating the shape composition comparison across basins (CB: Çoruh Basin, EBSB: Eastern Black Sea Basin, KB: Kızılırmak Basin, WBSB: Western Black Sea Basin, YB: Yeşilırmak Basin) (D).

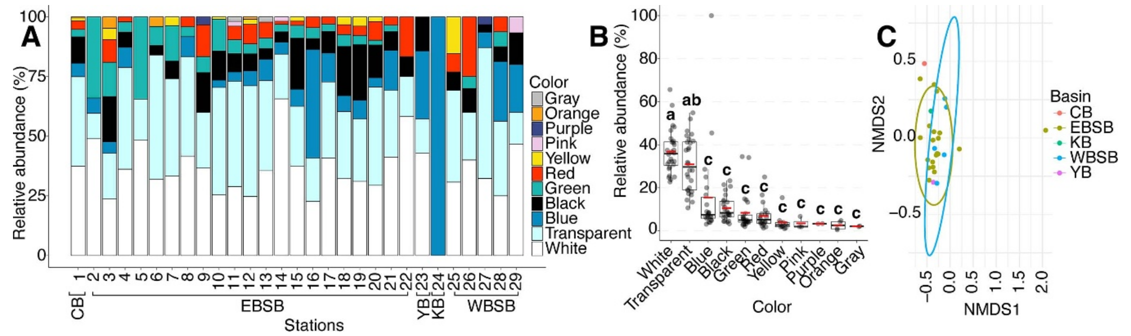

Figure 7. Color composition by station (A). Distribution and comparison of relative abundance of colors, with different letters indicating significant differences determined by Dunn's test (B). NMDS plot illustrating the color composition comparison across basins (CB: Çoruh Basin, EBSB: Eastern Black Sea Basin, KB: Kızılırmak Basin, WBSB: Western Black Sea Basin, YB: Yeşilırmak Basin).

Among the remaining colors, blue (15.5% ± 4.58%) and black (10.6% ± 1.17%) MPs had relatively higher shares, although their abundances were similar to each other. Color composition was consistent across basins, with no significant regional differences (ANOSIM, $p > 0.05$, figure 7(C)).

4. Discussion

Research on MP in Turkish inland waters remains limited relative to studies on marine environments. Existing research has primarily concentrated on isolated bodies of water, such as lakes [26], with some studies also addressing river systems [13, 32, 33]. Previous investigations have documented MP discharge along the Turkish Mediterranean coast [33] and noted a sharp increase in abundance following flood events [34]. Additionally, research has identified MP discharges from wastewater treatment plants [35] and river sediments flowing into the Black Sea [36, 37]. However, MP discharge from rivers along the Black Sea's southern coast remains infrequently documented.

This study highlights the role of river systems in MP pollution along the southern Black Sea coast, revealing significant spatial variability. The EBSB showed higher MP concentrations than the Western Basin, with hotspots at stations 12 and 13 likely linked to urbanization and industrial activity (table S1), consistent with global findings [38]. Seasonal tourism (June–August) exacerbates pollution, especially in heavily populated areas like Trabzon. Gül [39] observed increased MP abundance in coastal sediments during the tourist season, aligning with our findings. Elevated seasonal populations also likely boost airborne MPs, further impacting riverine systems [40].

In Türkiye, 46.4% (5 billion m^3) of urban discharge water is released into rivers (TurkStat, 2021). In particular, the Çoruh and EBSBs receive wastewater directly due to densely populated rural areas lacking urban discharge systems [36, 37]. Akdemir and Gedik [35] observed higher MP levels in EBSB discharge waters than in other basins. Population growth has led to variations in wastewater treatment practices across cities.

The EBSB primarily employs primary wastewater treatment, while secondary treatment is more common in the western regions and the Kızılırmak and Yeşilırmak basins. Secondary treatment is significantly more effective at removing MPs than primary treatment [35, 41, 42]. Consequently, higher MP concentrations are expected in the Eastern Black Sea and Çoruh basins. However, long-term monitoring is needed to better understand these spatial variations.

Table S1 details the annual run-off volumes from the sampled basins, showing that 1.86×10^{10}, 7.45×10^{10}, 1.9×10^{9}, 8.05×10, and 2.88×10^{10}MPs are transported annually from Türkiye to the Black Sea via rivers originating from the Çoruh, Eastern Black Sea, Yeşilırmak, Kızılırmak, and Western Black Sea basins, respectively. In a study conducted in the same sampling area, Akdemir and Gedik [35] reported that 1.24×10^{10} MP was discharged from wastewater treatment plants into the Black Sea. The results obtained served to reinforce the fact that rivers constitute the primary source of MPs [15] as well as discharge waters [35]. An analysis aimed at predicting the future outlook revealed that by 2050, the amount of MP delivered to the Black Sea by rivers will increase, with a significant proportion (30% to 64%) of the transported MP being sourced exclusively from Türkiye [43]. These factors are attributed to the rise in urbanization, sewage infrastructure, and inadequate waste management policies [24].

The predominant polymer types identified in this study were polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP). These polymers align with findings from other riverine MP studies (table 1). Moreover, PE and PP are among the most commonly used polymers in both global and Turkish markets (PAGEV, 2023).

A study on sediment from the Çoruh River basin reported a similar polymer composition, with PE (38.9%) and PET (24.7%) as the dominant types [37]. Research on sixteen rivers along the southeastern Black Sea also revealed that PET, PE, and PP were the most frequently detected polymers in sediment samples [36]. Akdemir and Gedik [35] further reported high concentrations of PET (34.9%), PP (32.4%), and PE (19.9%) in effluents from wastewater treatment plants discharging into the southern Black Sea and Marmara Sea.

Comparable findings have been observed across multiple Black Sea compartments, including surface waters [27, 28, 58], fish species [59, 60], mussels [61] and sediments [62–64]. Similar patterns have been reported in rivers across Asia and Europe [65, 66]. A comprehensive review of 29 studies on major European rivers and their tributaries identified a heterogeneous polymer composition attributed to varying methodologies, especially in MP analysis techniques [67].

The findings from this and similar studies highlight PET, PE, and PP as significant contributors to MP pollution. PET is heavily used in packaging, especially single-use plastic bottles, which accounts for its frequent presence in aquatic systems. PE and PP are extensively applied in packaging, plastic bags, and household goods, valued for their flexibility and chemical stability [68, 69]. Comparisons of polymer compositions across basins revealed no significant differences, suggesting that the widespread use and disposal of PET, PE, and PP across various industrial and consumer applications drive their prevalence in aquatic environments. This pattern is consistent across multiple regions and environmental compartments, underscoring the pervasive impact of these polymers on global aquatic ecosystems.

Determining the precise sources of MPs presents significant challenges; however, analyzing their shapes offers valuable insights into their potential origins. The morphology of MPs also influences their buoyancy, resulting in variable sedimentation or flotation rates in marine environments, which impacts their distribution across ecosystems [70]. Furthermore, MP shape affects both degradation [71] and bioavailability [72]. In rivers along the southern Black Sea coast, the shape profile of MPs is dominated by fibers (64.1% $\pm$ 2.62%) and fragments (28.3% $\pm$ 2.33%), both classified as secondary MPs. These shapes align with global freshwater and river studies (table 1). Studies on major European rivers, such as the Rhine, Danube, Po, Elbe, and Thames, similarly identified fibers as the most abundant MP type in some rivers [67]. In contrast, other studies have reported different dominant shapes. In the Cisadane River in Indonesia, fragments were the most prevalent MPs [73], while in the Rhine River, fibers represented only a small fraction (2.5%), with opaque spherules (45.2%) and fragments (37.5%) dominating the MP profile [74].

Synthetic textiles are a primary source of fiber-type MPs, releasing fibers during laundering that often enter aquatic systems post-treatment [35, 75]. Atmospheric deposition and tire wear in urban areas, particularly from synthetic rubber particles, are other major fiber sources [76, 77]. The international highway along the southeastern Black Sea likely adds significantly to the region's MP load.

Fragments, the second most common MP shape, originate mainly from the breakdown of larger plastic debris, which southeastern Black Sea rivers carry in abundance [16, 78]. The lack of significant variation in MP shapes between basins (ANOSIM, $p > 0.05$) suggests widespread distribution from common sources and pathways.

MP size significantly influences their transport and bioavailability. MPs $<$200 μm exhibit greater mobility and are more readily ingested by aquatic organisms due to their size similarity to prey, facilitating bioaccumulation and food web transfer [79–81].

In this study, the size distribution of MPs predominantly comprised particles within the 100–1000 μm range, representing the largest fraction at 41.3% $\pm$ 5.49% across all sampled stations. A parallel study in lakes within the Kızılırmak basin found that 80.49% of MPs ingested by *Carassius gibelio* were smaller than 2000 μm [82]. Additionally, a Black Sea study on a commercially important species, the

Table 1. Reported concentrations of microplastics (MPs) in river waters from various global studies, including the present study's findings from rivers in the Black Sea region. The table provides a comparative overview of MP concentrations, polymer types, and shapes to contextualize the current study within the broader field of riverine microplastic research. Data limitations specific to Black Sea-linked rivers are acknowledged.

Country	Study river	Mesh size (μm)	Concentration (MPs m^{-3})	Polymers	Shape	References
China	Zhangjiang River	330	246	PP, PE, PS, PES, PET, PE, PP	Fragment, fiber, pellet, line, film, foam	[44]
Indonesia	Surabaya River	333	1.47–43.11	LDPE, PP, PS, PE, PET	Film, fragment, fiber, foam, pellet	[45]
Japan	Japanese Rivers	100–300	1.62–1.85	PE, PET, PP, PS	Fiber, pellet, sheet, sphere	[46]
Malaysia	Cherating River	100	0.0042	Not identified	Fragment film, foam, line, pellet	[47]
France	Rhône and Têt Rivers	333	12–42	PEST, PP, PE, PS, Acrylic, PA	Fiber	[38]
Ecuador	Tropical Andean rivers	250	0.72–1186	Not identified	Fiber, fragment, film	[48]
Colombia	Magdalena River	20	0–14	PP, PE, PS, PET, nylon	Fiber, fragment, pellet	[49]
India	Lower Ganga River	300	0.38–0.68	PE, PP	Fragment, film, foam, filament	[50]
Canada	North Saskatchewan River	53	4.6–88.3	PP, PE, PEST, PU, PVC, acrylic, PVA	Fiber, fragment, film, sphere	[51]
Poland	Vistula River	55	1600–2550	PS, PP, nylon	Fiber, fragment, microbead	[52]
Bangladesh	Karnafully river	20	570–6630	PE, PET	Fragment, fiber, film, pellet	[53]
China	Yangtze River Basin	48	1270	Not identified	Fiber, film, fragment, bead, and foam	[54]
Türkiye	Various rivers in Mersin Bay	26	293	PE, PVC, Cellulose, PP	Fragment, film, fiber, and others	[33]
Türkiye	Various rivers in Antalya Bay	333	0.2–1.4	PP, PE, PET, PVOH	Fiber, film, fragment, and foam	[55]
India	Godavari River	Bulk	3900	PP, HDPE, LDPE, ABS, EVA, PS, and nylons	Fiber, pellet, filament, film, foam	[56]
Türkiye	Ergene River	45	4650–6900	PET, PA, PE, PS, PP, polyisoprene (PI)	Fiber, fragment, foam, pellet, rubber	[32]
Türkiye	Munzur and Pülümür River	333	0.04–28.21	PE, PS, PP, PET	Glitter, fiber, film and fragment	[13]
South Africa	Vaal River	55	0.13–2.52	HDPE, LDPE, PP	Fiber, film, fragment, pellet	[57]
Türkiye	Various River in Black Sea region	200	9.63	PET, PE, PP, PA, others	Fiber, fragment, films, sphere	This Study

European anchovy, reported that 73% of ingested MPs were under 1000 μm [60]. Consistent findings on MP size distribution have been documented in various aquatic species [64, 83], as well as in water [28] and sediment samples [36, 37, 63]. These data emphasize the predominance of smaller MPs in diverse aquatic environments and their potential ecological impacts through bioavailability and trophic transfer.

This study identified eleven distinct colors of MPs, with white and transparent being the most prevalent. Although no significant variation in color composition was observed across basins, prior studies in the Black Sea have reported considerable color variability in MPs. Despite this randomness, MP color can offer insights into ecological interactions and pollutant behavior. Specifically, MP color influences interactions with aquatic organisms and environmental processes. For example, Horie *et al* [84] reported species-specific preferences in MP ingestion among certain fish species: *Chrysiptera cyanea* preferred red MPs, *Palaemon japonicus* favored blue and gray, and *Rhynchocypris ocellatus* selected red and yellow MPs. Conversely, species such as *Hemiculter tsurugae, Pseudorasbora parva*, and *Misgurnus anguillicaudatus* displayed no distinct color preference. These findings suggest that fish species with selective feeding behaviors may be more inclined to ingest certain MP colors. Additionally, an experimental study demonstrated that green MPs have a higher affinity for marine lipophilic phycotoxins (MLPs), indicating that MP color may affect their capacity to carry pollutants [12]. Such findings reinforce the notion that rivers act as vital pathways for MP pollution into the Black Sea, aligning with global research showing that riverine MPs not only enter marine systems directly but also serve as a consistent source of contamination [43]. Due to the semi-enclosed nature of the Black Sea, MPs can persist in the ecosystem for extended periods, potentially impacting pelagic and benthic ecosystems over the long term.

5. Conclusion

This study highlights riverine MP pollution along the southern Black Sea coast, with findings indicating higher MP concentrations in the EBSB due to urbanization, industrial activities, and summer tourism. Dominant polymers, primarily from consumer packaging, reflect widespread plastic use, while fibers and fragments suggest secondary MPs as key pollution sources. Smaller MPs (100–1000 μm), which pose higher ingestion risks, were abundant, raising concerns about bioaccumulation, biomagnification, and potential human health impacts via seafood consumption.

Mitigating Black Sea MP pollution requires targeted strategies, including improved waste management, stricter plastic regulations, enhanced wastewater treatment, and public awareness, especially in high-tourism areas. Coordinated efforts are essential to protect aquatic ecosystems and human populations dependent on these resources.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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CRediT authorship contribution statement

Yahya TERZİ: Conceptualization, Data curation, Formal analysis, Writing-original draft, Writing—review & editing, visualization, **Rafet Çağrı ÖZTÜRK:** Conceptualization, Investigation, Writing—review & editing, Project administration, **Ahmet Raif ERYAŞAR:** Investigation, **İlhan YANDI:** Investigation, **Ahmet ŞAHİN:** Investigation, **Fatih Yılmaz:** Investigation, **Kenan GEDİK:** Conceptualization, Project administration, Funding acquisition,Writing- Review & Editing, **Sedat Gündoğdu:** Writing-original draft, Writing—review & editing, visualization.

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