



Microplastic Contamination of the Seawater in the Hamsilos Bay of the Southern Black Sea

Ayşah Öztekin · Funda Üstün · Levent Bat · Ahmet Tabak

Received: 23 November 2023 / Accepted: 5 May 2024
© The Author(s) 2024

Abstract The marine ecosystem is severely threatened by microplastics. The entire marine environment of the Black Sea is contaminated with both macro- and microplastics but the contamination of the water column with this pollutant has received less attention. This study aims to obtain data on the microplastic abundance, and vertical and temporal distribution of the microplastics in the water column of Hamsilos Bay which is a natural protected area, and an important area for fishery and tourism on the Sinop coast in the Black Sea. This study was carried out for 12 months in 7 stations. Microplastic abundance varied among 5.58 ± 6.12 – 8.12 ± 9.17 pieces/m³ in and 1.74 ± 0.80 – 21.07 ± 3.84 pieces/m³ in stations. The dominant microplastics were fibre by shape (73.92%), 1–2 mm (28.35%) by size class, and blue (37.98%) by colour. The synthetic polymers in the examined microplastic samples of this study were PET (47%),

PE (34%), HDPE (10%), PVC (7%) and PS (2%). The results of this study show that the coastal area is widely contaminated with microplastics. Microplastic pollution is an increasingly significant environmental issue that poses a threat to the Black Sea which is particularly vulnerable to microplastic pollution. The region is an important ecological hotspot in the Black Sea and this study can provide valuable insights into the extent of microplastic pollution and will contribute to the literature on the evaluation of microplastic pollution in marine ecosystems. These types of investigations; efforts to address the environmental challenges facing the Black Sea, including the development of programs to reduce pollution, increase sustainability, and support the protection of the region's natural resources, are crucial to its continuity.

Keywords Microplastic · Fibre · Polyethylene · Black Sea · Water column

A. Öztekin (✉) · F. Üstün · L. Bat
Fisheries Faculty, Department of Hydrobiology, Sinop University, Sinop, Türkiye
e-mail: aysahvisne@gmail.com

F. Üstün
e-mail: fundastun@gmail.com

L. Bat
e-mail: leventbat@gmail.com

A. Tabak
Faculty of Pharmacy, Department of Analytical Chemistry, Ondokuz Mayıs University, Samsun, Türkiye
e-mail: ahmettabak@omu.edu.tr

1 Introduction

Plastic use has come with severe environmental, social, economic, and health consequences. Every year, approximately 8 million tonnes of plastics end up in the oceans (Jambeck et al., 2015). Plastic pollution has become an unignorable pollution problem. Plastics enter the aquatic environment in various sizes, and they are defined by their sizes such as macroplastics, mesoplastics, microplastics, and

nanoplastics (GESAMP, 2019; Hanke et al., 2013). Microplastics are defined as plastic particles between 5 mm -1 µm in size (Frias and Nash, 2019). Microplastics enter the marine environment via produced in microplastic size (primary microplastics) or fragmentation of larger plastic debris (secondary microplastics), and through mainly land-based activities, especially via runoffs (Boucher & Friot, 2017; GESAMP, 2019).

Microplastics are well-known as a rising threat to the marine environment and have been reported in the marine environment since the 1970s (Carpenter & Smith, 1972). It has been reported in different marine environments all over the world: on the sea surface, in the water column, and sediments (Aliabad et al., 2019; Cincinelli et al., 2019; Dekiff et al., 2014; Peng et al., 2017).

Microplastics are widely dispersed in the marine environment and are transported over great distances from their source by wind and water movements (Dai et al., 2018; Ryan et al., 2009). Microplastics may accumulate on the seafloor, and sink with fouling or dispersing the water column (Dai et al., 2018; Kaiser et al., 2017; Lusher et al., 2015; Woodall et al., 2014). So, it can be useful for determining the long-term fate of microplastics in marine environments via monitoring the microplastic distribution in the water column and on the seabed.

The presence of microplastics is severely threatened to the ecosystem and their availability of all sizes allows a wide variety of marine organisms to encounter microplastics. It is reported that it interacts with the organisms at the bottom of the marine food web (Long et al., 2015; Rodrigues et al., 2021). Microplastic consumption has been reported in many organisms (Carlin et al., 2020; Nelms et al., 2019; Xu et al., 2020; Zhu et al., 2019). Microplastics have negative effects on organisms, and the effects on growth and reproduction are just a few of them (Jeong et al., 2016; Ogonowski et al., 2016). Toxic pollutants like persistent organic pollutants and trace metals etc. tend to bind to microplastics (Liedermann et al., 2018; Teuten et al., 2007). These microplastics, which are contaminated or contain pollutants, may cause negative effects on living things as a result of consumption.

Microplastics that have floated, beached, or sedimented on the seafloor, are relatively well-investigated (Cincinelli et al., 2019; Van Cauwenbergh

et al., 2013; Wessel et al., 2016). On the other hand, the microplastics within the water column have received less attention (Dai et al., 2018; De La Fuente et al., 2021). To understand the fate and migration of microplastics in the marine environment, all relevant parts of marine ecosystems are needed for quantitative and qualitative monitoring.

The Black Sea is facing significant environmental challenges, including pollution and the existence of microplastics. The sources of pollution in the Black Sea are diverse, including industrial and agricultural activities, shipping, urbanization, and other anthropogenic activities, as well as atmospheric deposition (Bat et al., 2018). One of the most important environmental challenges in the Black Sea is plastic pollution (Bat & Öztekin, 2022). The entire marine environment of the Black Sea, from the seawater to the sediment and beaches is contaminated with both macro- and microplastics, and plastic consumption of various organisms has also been reported (Aytan et al., 2016, 2022; Bat et al., 2022; Eryaşar et al., 2022; Öztekin & Bat, 2017; Terzi et al., 2022). Like many coastal cities in the Black Sea region, Sinop is facing environmental challenges related to pollution and the degradation of natural resources (Bat et al., 2018). The city is home to several activities, including fishing, agriculture, and tourism, all of which can have an impact on the coastal environment. In the Sinop coasts, the possible litter sources were reported as improper waste and sewage management, river runoff, tourism, fishing, aquaculture, and shipping and litter items primarily from land-based sources (Bat et al., 2022). Fishing and tourism are prominent activities in the province of Sinop (Bat & Gökkurt Baki, 2014), Sinop has a small industry. Tourism and fishing can contribute to microplastic pollution in several ways. An important source of microplastic pollution in coastal areas is fishing activities; abandoned, lost, or discarded fishing gear may result in the release of microplastic particles into the marine environment (Wright et al., 2021; Xue et al., 2020).

Investigations on the presence of microplastics in seawater have focused more on the sea surface, considering the accumulation of plastics on the surface due to their low density, and it has been similar in the Black Sea (Aytan et al., 2016; Berov & Klayn, 2020; Eryaşar et al., 2021; Mukhanov et al., 2019; Pojar et al., 2021; Terzi et al., 2022). However, considering the low salinity of the Black Sea (‰17–18), it reveals

the fact that microplastics can also be found intensively in the water column (Öztekin & Bat, 2017) so the vertical distribution of microplastics should not be ignored and it can be useful for determining the long-term fate of microplastics at the marine environment. However, there are inadequate investigations on the vertical distribution of microplastic particles in the Black Sea marine environments (Aytan et al., 2020, 2022; Öztekin & Bat, 2017). Hamsilos is a coastal ria located in the province of Sinop in northern Türkiye, which is connected to the Black Sea. It is an important ecological and cultural area that has been declared a Natural Protected Area in 2007 (MAF, 2023). Efforts are underway to address environmental challenges and protect the unique biodiversity of Hamsilos. Last few years, the Turkish Ministry of Environment and Urbanization launched a comprehensive restoration and conservation project for the Hamsilos, which includes measures to improve water quality, regulate land use, and promote sustainable tourism in the area. Within this scope, the purpose of the current study is to gather more information on microplastics, their abundance, and the vertical and temporal distribution, in the seawater of Hamsilos Bay which is a first-degree natural protected area, an important area for fisheries and tourism on the Sinop coasts of the Black Sea. In this way, it is aimed to reveal the presence of microplastic contamination in this unique area located on the Turkish coast of the Black Sea.

2 Material-Method

2.1 Survey Area and Survey Strategy

Sinop is a large peninsula, and this peninsula consists of two extensions, one being İnceburun, which is the northernmost tip of Türkiye, and the other being Boztepe, where Sinop city center is located in the northeast of the peninsula. Hamsilos Nature Park is located in the İnceburun extension of these extensions (Üstün, 2019).

Hamsilos Nature Park is a first-degree natural protected area (MAF, 2023; Üstün, 2019). Hamsilos Bay is a ria coast, an inverted, L-shaped, long, and narrow bay that reaches the open sea and it is 250 m long, 125 m wide, and 12 m depth (Akkan, 1975; Üstün,

2019). Hamsilos is home to a rich variety of biota (Üstün, 2019; Üstün & Birinci Özdemir, 2019).

The sampling was conducted between July 2015 to June 2016 on monthly in Hamsilos Bay (Fig. 1). Sampling was performed with a plankton net (50 cm mouth diameter and 112 µm mesh size). Vertical tows were made from different depths (A: 2 m; B: 4 m; C: 9 m; D: 13 m; E,F,G: 30 m). The samples were stored with fixed in a 4% formalin–seawater solution (Üstün, 2019).

2.2 Laboratory Analysis

The samples were rinsed from a sieve (20 µm mesh size). The material on the sieve was transferred to the beaker. The collected sample was firstly peroxidized by Fenton reagent to remove organic material. This procedure was performed according to Masura et al. (2015) with some modifications. 20 mL 0.05 M Fe (II) solution was added to the sample and then, 20 mL 30% Hydrogen peroxide (H₂O₂) solution was added to digest the organic material. The samples were left at 40–45 °C until all visible organic material was digested. After digestion was completed, the density separation (with NaCl) was performed to remove the inorganic particles in the samples. Samples were filtered on filter papers (GF/C) and examined under a stereomicroscope (Nikon SMZ745). Microplastics were categorized according to shape (film, fibre, fragment, foam, and pellet) and colour. The sizes of microplastics were measured individually.

Precautions were taken to detect and prevent the potential risk of contamination. All laboratory analysis was performed with cotton laboratory coats in a fume hood and an examination cabin. All equipment used after was washed with distilled water (two times) and covered with aluminum foil to prevent contamination. Blank samples were used for procedural contamination and clean filters were used for airborne contamination. If contamination was detected, similar particles were removed from the data set.

2.3 Polymer Analysis

FTIR spectra of microplastic samples were recorded in the region of 4000–450 cm⁻¹ by using a Fourier Transform Infrared Spectrophotometer (Shimadzu, IR Spirit+QATR-S System). FTIR spectrum of each analysed sample in comparison with literature FTIR

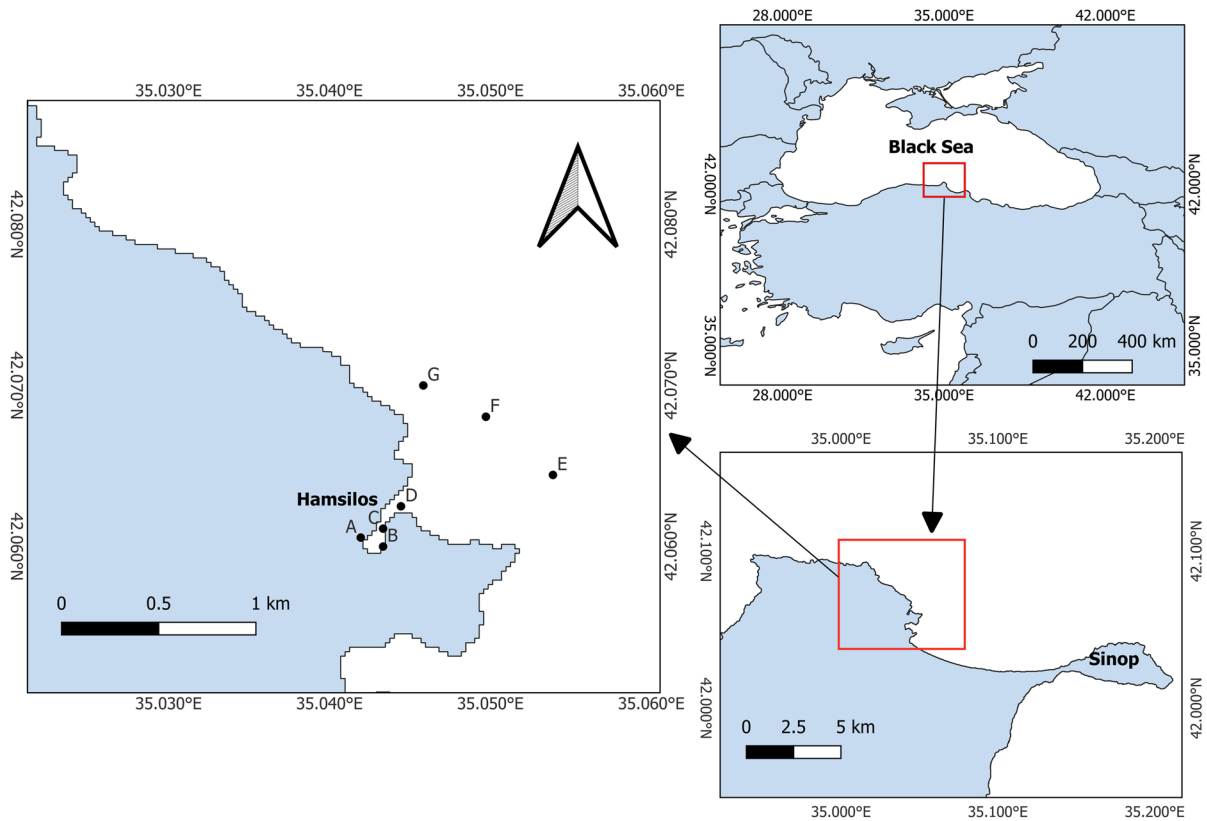


Fig. 1 Sampling points in Hamsilos Nature Park

data pointed out the presence of microplastic particles. In total 42 particles were analysed and samples with a spectral similarity of at least 70% were accepted.

2.4 Data Analysis

The microplastic density in the water column was presented as the mean \pm standard deviation pieces/ m^3 . The percentage distribution of shapes and colours was determined. All microplastic sizes were measured individually and classified according to 7 size classes (<0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, 3–4 mm, 4–5 mm). The distribution of data was tested with the Shapiro–Wilk test. The non-parametric Kruskal Wallis test was used to determine spatial and temporal variations. The relationship between the depth and the number of microplastics was evaluated with Spearman rank correlation. All tests were performed in IBM SPSS and the p-value was accepted as 0.05.

3 Results and Discussion

In total 3194 microplastic particles were found in all samples. In the study carried out for 12 months, microplastic abundance was found minimum in October (5.58 ± 6.12 pieces/ m^3) and maximum in February (8.12 ± 9.17 pieces/ m^3) (Fig. 2B). In general, the distribution of microplastics in the months was close to each other and there were no statistical differences in the months ($p > 0.05$).

The investigation was conducted on 7 different stations and 5 different depths. Microplastic abundance was found at minimum in station F in 30 m (1.74 ± 0.80 pieces/ m^3) and maximum in station A in 2 m (21.07 ± 3.84 pieces/ m^3) (Fig. 2A). E, F, and G stations (all of them 30 m depth) were similar in themselves, and all stations were statistically different from each other except for these stations ($p < 0.05$). It was observed that the microplastic abundance decreased as the depth increased. There was a significant negative relationship between depth and microplastic abundance ($p < 0.05$; $R: -0.92$).

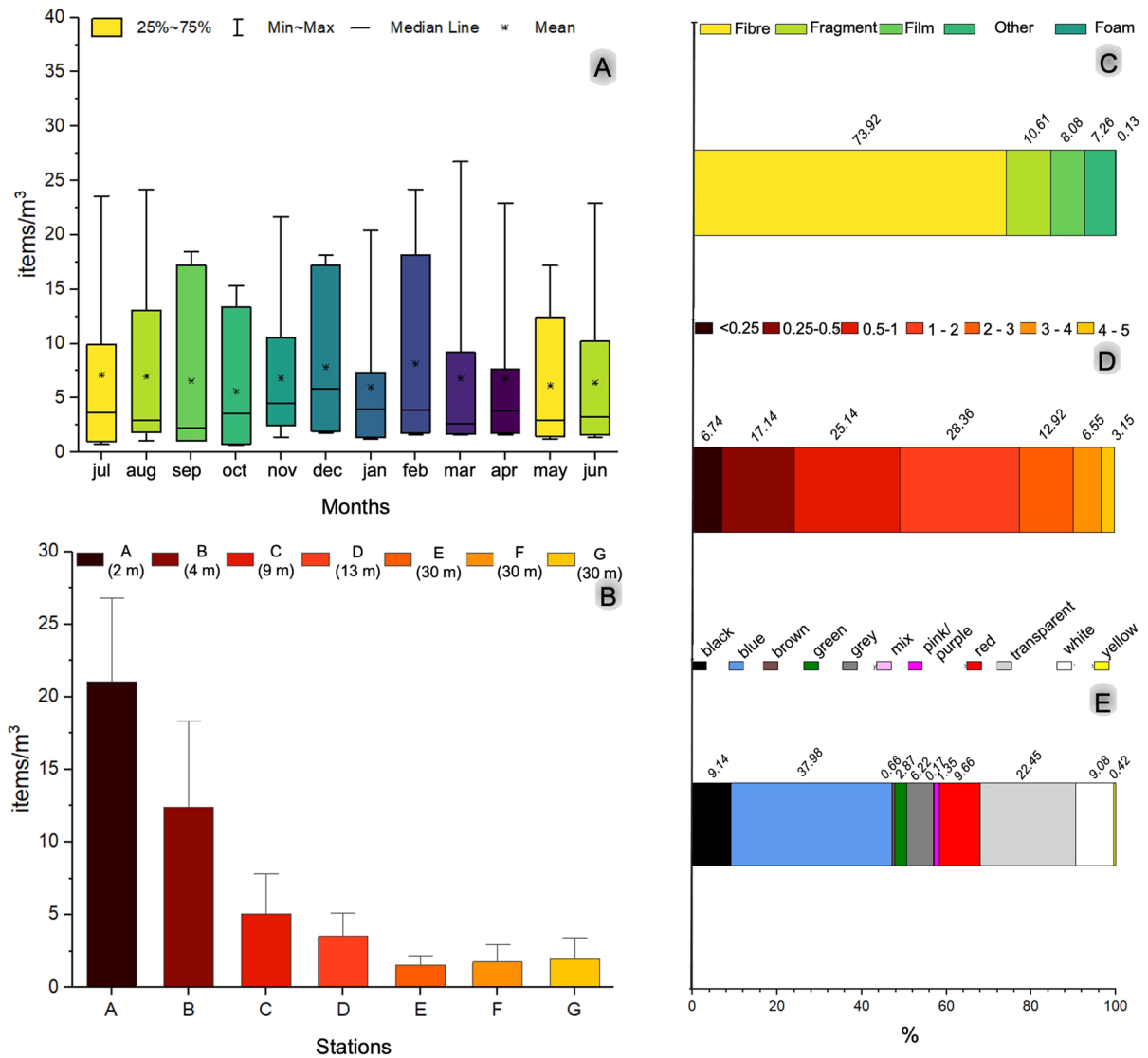


Fig. 2 Temporal (A) and spatial (B) variations of microplastics and shape(C), size (D), and colour (E) distribution of microplastics in Hamsilos Bay

The investigations on microplastic pollution have placed more emphasis on the sea surface, but some studies have found that the amount of microplastics in the water column is higher than the amount of microplastics on the sea surface (Öztekin & Bat, 2017; Piazzolla et al., 2023; Wang et al., 2022). The water column research was conducted in limited numbers on the Black Sea coasts (Aytan et al., 2020, 2022; Öztekin & Bat, 2017). So, all parts of the marine environment are needed for investigation to understand the distribution of microplastics in the marine environment.

Sinop coasts are indented shores and are not steep in comparison to the Eastern Black Sea shores and there are no harbors protected by bays and gulfs as far as Sinop in the Black Sea Turkish coasts that start from Hopa and end in the Istanbul Strait (Öztekin et al., 2020). Hamsilos is a coastal ria, and the region is sheltered and does not have direct pollution resources. However, it is seen that Sinop is exposed to an intensive amount of litter due to the current regime of the Black Sea (Öztekin & Bat, 2020; Bat et al., 2022). In this study, it has been demonstrated how

even such an enclosed area with no direct pollutant source can be contaminated with this pollutant. It is seen that plastic pollution is effective not only at the pollution source but also at points far away from the pollutant source.

Plastics may be transported between zones due to their varied physical characteristics of plastics as polymer density, and mechanical, chemical, and biological processes, such as bio-transport and biofouling, as well as waves and currents (GESAMP, 2019). Depending on their diameter and relative buoyancy, surface winds can re-distribute buoyant particles by mixing the upper layers of the water column (GESAMP, 2019). It was observed that there was a negative relationship between depth and microplastic abundance. Microplastic abundance increased closer to the shore. Similar results reported by Aytan et al. (2022) and Öztekin and Bat (2017) in the Black Sea, by Güven (2022) in the Mediterranean Sea Türkiye coasts and Piazzolla et al. (2023) found microplastic abundance higher in the column samples in the coastal stations in the Mediterranean Sea. The water column samples were taken from 5, 15, and 30 m by Öztekin and Bat (2017) and 5, 10, and 15 m by Güven (2022), and in both researches most polluted station was found at 5 m, the closest station to the coast. Aytan et al. (2022)'s closest station to the shore is at a depth of 50 m, relatively deeper than even the deepest station of the current study, and this coastal station is again the most polluted. The distribution of buoyant plastics may be affected by winds and accumulate more heavily on shores downwind of them (Browne et al., 2010; Piazzolla et al., 2023; Sadri & Thompson, 2014; Zhang, 2017). Additionally, strong winds and corresponding wave action could mix the water vertically and resuspend plastic debris from the bottom (Kukulka et al., 2012; Reisser et al., 2015; Zhang, 2017). This may have caused a higher microplastic abundance, especially in shallow stations where the effect of wave effect is higher.

In this study, samplings were conducted monthly, at all sampling dates encountered with microplastics, and there was no statistically significant temporal difference. The temporal distribution of microplastic abundance in the region does not show any tendency. A similar situation is also mentioned in water column samples by other researchers (Aytan et al., 2022; Güven, 2022). Microplastics are unique pollutants, each from different sources, and different degradation

processes, and the main reason for their existence in nature is human, but their distributions are affected by natural conditions (current, wind, etc.). A natural factor such as sudden rainfall or a picnic held by a family in an area close to the sampling point seriously affects their existence in that area. Their presence in nature is quite variable. So, their presence in the natural environment is quite variable. For this reason, there was no relationship in this study by temporal aspect. Therefore, as in most investigations on microplastics in the natural environment, the standard deviations in this study are relatively high.

Five shapes of microplastics (fibre, film, fragment, foam, paint particle) were encountered in water samples (Fig. 3). The dominant microplastic shape was fibre at 73.92 (± 11.86)% and followed by fragment (10.61 ± 11.53 %), film (8.08 ± 8.78 %), other (7.26 ± 7.89 %), foam (0.13 ± 0.14 %) (Fig. 2C). The particles evaluated in the other category consist only of paint particles.

One of the major sources of microplastics in marine environments is the breakdown of larger plastic items, such as bottles, bags, and fishing gear and these items break down into smaller particles with the effects of various factors (Hidalgo-Ruz et al., 2012). Five shapes of microplastics (fibre, film, fragment, foam, paint particle) were encountered in water samples and the dominant microplastic shape was fibre (73.92%) followed by fragment (10.61%), film (8.08%), paint particle (7.26%), foam (0.13%). It is mentioned that wastewater discharge can be found in areas with high fibre content, and the existence of waste disposal sites in areas with high amounts of fragments (Kang et al., 2018; Wang et al., 2017; Irfan et al., 2020). Sewage systems are one of the major sources of microplastic pollution, lots of microplastic fibres could pass into the sewage systems via the washing of synthetic clothes (Browne et al., 2011). Considering the source factor, microplastics in the research area were mostly fibre and this supports the determination that they may be formed as a result of the discharge of sewage waters into the marine environment. Plastics are stored in landfills in terrestrial environments due to inappropriate waste management and these environments create a suitable area for the formation of secondary microplastics (Nizzetto et al., 2016). Microplastics are transported along rivers and coastal areas because of activities such as domestic, industrial, and transportation in the

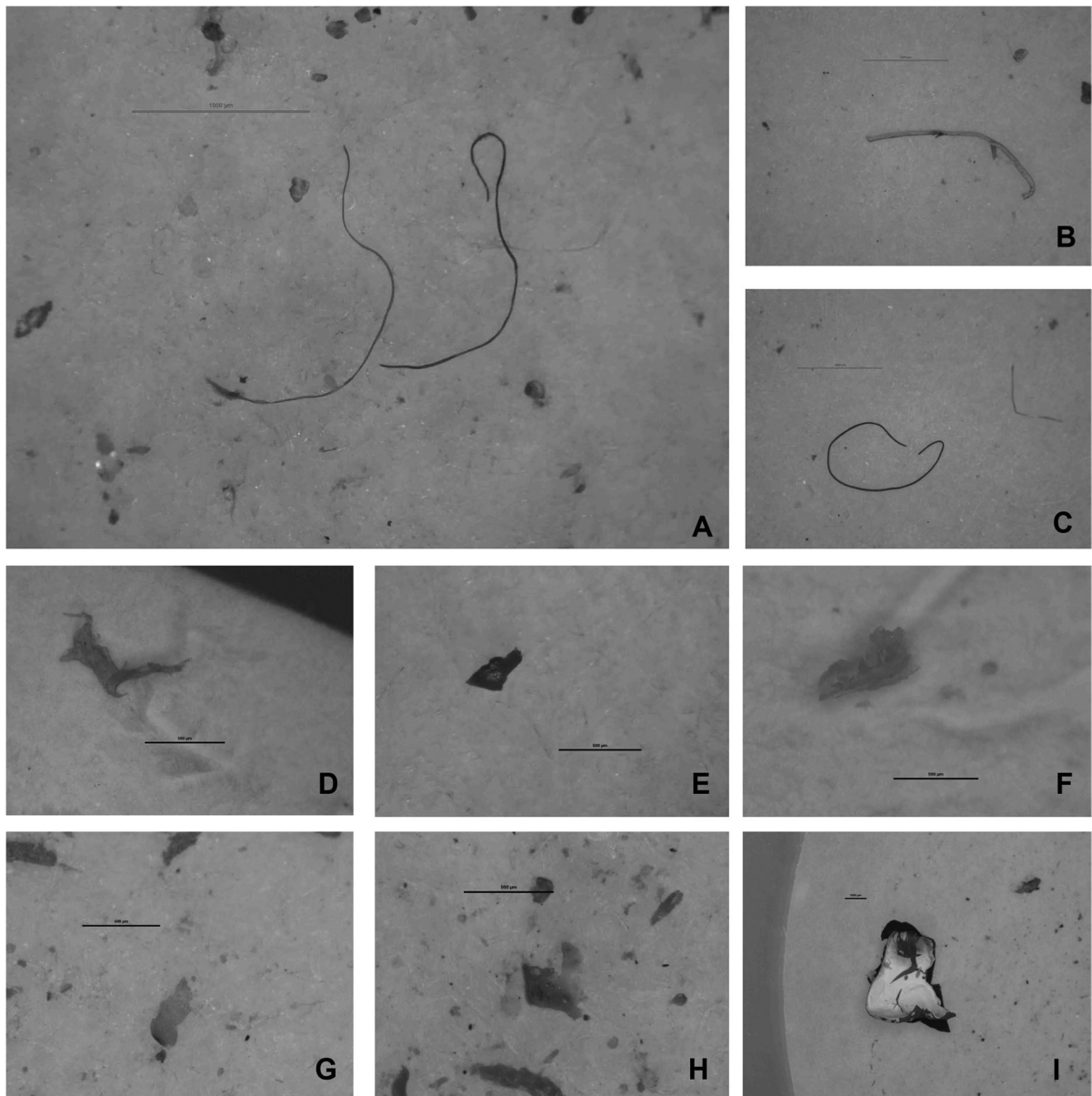


Fig. 3 Microplastic representatives found in the water column (A-C: fibre; D-F: fragment; G,H: film; I: paint, red scale bars = 1 mm and black scale bars = 0.5 mm)

terrestrial environment (Horton et al., 2017; Siegfried et al., 2017). The paint particles were also found during the study, all paint pieces with the same colour as the colour of the sampling vessel were excluded from the data set during the analysis, so the amount of paint particles may have been underestimated. Hamsilos Bay is visited by tourist boats during the summer months due to its natural beauty. The region

is very sheltered against adverse weather conditions. This bay is used as an anchorage and resting area by fishing boats during the fishing season. Intense fishing activities continue in the region and there is also a fishing port nearby. Therefore, Wang et al. (2018) suggested that the dominance of fibres might be related to the breakdown of fishing gears such as nets and ropes.

The minimum and maximum lengths and mean values were calculated from individually measuring microplastics, in addition, microplastics were collected in 7 groups according to their size classes. The size of microplastics ranged between 0.129 mm and 4.960 mm and was mean 0.135 ± 0.106 mm. The percentage distribution of size class for <0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, 3–4 mm, and 4–5 mm was $6.74 \pm 2.96\%$, $17.14 \pm 3.92\%$, $25.14 \pm 5.25\%$, $28.35 \pm 1.86\%$, $12.92 \pm 1.40\%$, $6.55 \pm 0.77\%$, $3.15 \pm 1.02\%$, respectively (Fig. 2D).

The sampling of microplastics in the marine environment (sea surface, water column, sediment) requires a variety of approaches. Microplastic samples were generally collected with plankton nets and also Niskin bottles in the investigations conducted in the water column in the Black Sea (Aytan et al., 2020, 2022; Bat & Öztekin, 2022; Öztekin & Bat, 2017). The size of the mesh on the plankton nets limits the size of the filtered particles and the nets also enable sampling of larger amounts of water (Bat & Öztekin, 2022; Dris et al., 2018). In the present study, the mesh size of the net was 112 μm and this mesh opening limits the size of the sampled plastics. The non-selective samplers (like Niskin) also sample microplastics at smaller sizes as they catch regardless of size. The investigation of Dai et al., (2018) showed that the microplastic sizes changed with depth in the water column, and the fraction of the size 300 μm increased with depth, which they attributed to fast biofouling on the tiny microplastics. Therefore, salinity is also effective on the sinking behaviour of microplastics (Kowalski et al., 2016) and it is possible to encounter high amounts of microplastics in the water column and sediment in the Black Sea, which has relatively low salinity. So, to understand the fate and migration of microplastics in the marine environment, all relevant parts of marine ecosystems are needed for quantitative and qualitative monitoring.

Eleven colours of microplastics (black, blue, brown, green, grey, mixed, pink/purple, red, transparent, white, and yellow) were found in the water samples. The dominant colours were blue (37.98%) and transparent (22.45%), then followed by red (9.66%), black (9.14%), white (9.08%), grey (6.22%), green (2.87%), pink/purple (1.35%), brown (0.66%), yellow (0.42%), mix (0.17%) (Fig. 2E). The presence of blue and transparent microplastics as dominant colours in water samples has also been reported by

many researchers (Aytan et al., 2022; Dai et al., 2018; Kama et al., 2021). It is mentioned that transparent microplastics may originate from disposable plastics such as disposable and single-use plastic while coloured microplastics may originate from long-lasting plastic products (Andrady, 2017; Eo et al., 2019; Mülayim et al., 2022; Xiong et al., 2018; Yang et al., 2021). Karami et al. (2017) reported that the optical identification of MPs is a crucial step and the optical assessment of the microplastics. Since transparent or white MPs are common in natural environments (Shaw & Day, 1994; Ivar do et al., 2013), optical analysis of the MPs on the filter membrane may be interfered with by the presence of undigested and discolored organic components (Karami et al., 2017). Therefore, it has been reported that color changes may occur during the oxidation step applied during laboratory processes (Karami et al., 2017; Nuelle et al., 2014) and this situation should not be ignored. Applying H_2O_2 (30%–50 °C) resulted in a partial breakdown and discoloration of the biogenic particles and changed the color of PET (Karami et al., 2017; Nuelle et al., 2014). However, Yu et al. (2019), were reported that almost none of the studied polymers were impacted by the digestion process, with the exceptions of a slight color change (white to light yellow) and a slight surface corrosion (rough to smooth) of polystyrene particles. Therefore, any changes due to the oxidation step applied during this study were ignored.

The importance of colours in the classification of microplastics derives from their potential to be easily mixed with food by various organisms, thus contributing to the possibility of ingestion (Bat & Öztekin, 2022). The feeding behavior with microplastics has been observed in commercial fish species and their larvae which are visual predators that consume with small zooplankton or other crustaceans, most similar to their prey (Rodríguez-Seijo and Pereira, 2017). The most common colour in some fish species was blue, and it has been suggested that this colour preference may be due to the colour of the zooplankton group which is the prey of fish (Ory et al., 2017). This study was carried out during zooplankton sampling and using a zooplankton net, therefore this pollutant coexists with zooplankton. Hamsilos is home to a rich variety of biota, including zooplankton (Üstün, 2019). Microplastics have been found in a wide range of marine organisms, including zooplankton and

studies have shown that microplastics can be ingested by different zooplankton groups, such as copepods and other small crustaceans (Desforges et al., 2015; Svetlichny et al., 2021; Aytan et al., 2022). Zooplankton are an important food source for many fish and other organisms, and their ingestion of microplastics can have implications for the transfer of microplastics up the food chain. This can lead to potential risks to human health through the ingestion of microplastic-contaminated seafood.

From FTIR spectra of the analysed microplastic samples (Fig. 4), it can be concluded that polyethylene terephthalate (PET) and polyethylene (PE) in ratios of 47% and 34%, respectively were determined as the main synthetic polymers. The obtained FTIR data can be also attributed to other synthetic polymer types of high-density polyethylene (HDPE, ratio: 10%), polyvinyl chloride (PVC, ratio: 7%), and polystyrene (PS, ratio: 2%).

Polymer density affects the distribution of plastics in the aquatic environment, it is also important to know polymer types to understand how microplastics are transported at the surface and depths. The spectroscopic identification of macro- and microplastics provides information about the polymer component. In this study, the polymer analysis results showed that the dominant polymers were PET (47%) and PE (34%), followed by HDPE (10%), PVC (7%) and PS (2%). It is known that polyethylene and its derivatives can be used in the production of food/beverage packaging, insulation for wires and cables, garbage and grocery bags, bottles, toys, houseware, chair arms, casters, and furniture components, etc. In the IR spectrum of PET, the aromatic C-H stretching band at 3057 cm^{-1} , the OH stretching band at 3425 cm^{-1} , the C-H stretching band (for alkyl group) at 2965 cm^{-1} , the C=O stretching band at 1729 cm^{-1} , the vibrations of aromatic ring in the range $1600\text{--}1400\text{ cm}^{-1}$ and the vibrations of terephthalate group (OOCC₆H₄-COO) at 1239 and 1120 cm^{-1} were clearly seen (Chen et al., 2013; Edge et al., 1996; Pereira et al., 2017; Silverstein & Webster, 1998). The IR spectrum of PE exhibited the asymmetric (2918 cm^{-1}) and symmetric (2852 cm^{-1}) CH₂ stretches, CH₃ symmetric (1375 cm^{-1}) and rocking (723 cm^{-1}) deformation bands (Zbinden, 1964; Haslam et al., 1983; Gulmine et al., 2002). The asymmetric CH₃ stretching band (2965 cm^{-1}), the asymmetric (2918 cm^{-1}) and symmetric (2853 cm^{-1}) CH₂ stretches, CH₃

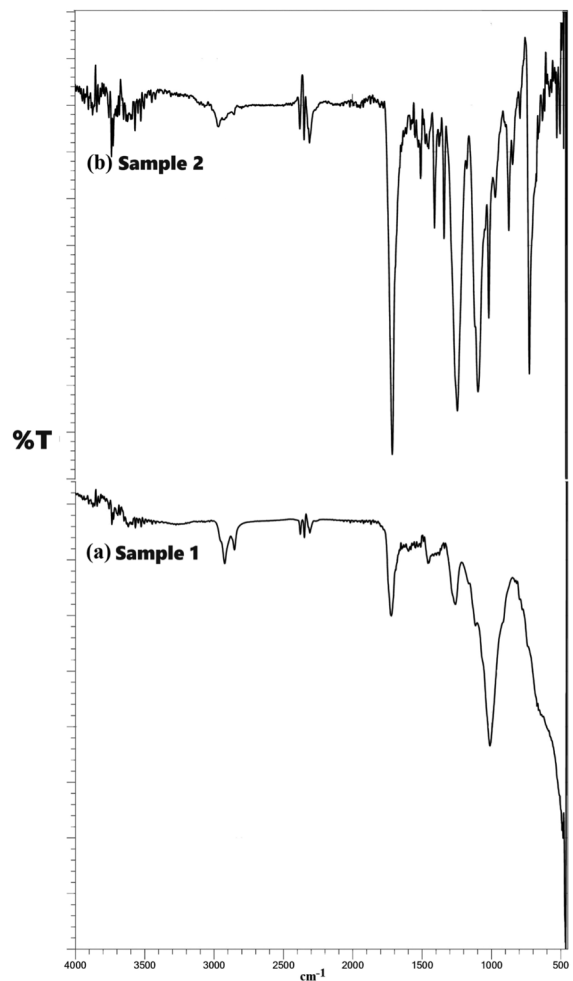


Fig. 4 FTIR spectra of (a-b) some samples in the examined particles

umbrella bending mode (1376 cm^{-1}) and split CH₂ rocking vibrations (730 and 721 cm^{-1}) for IR spectrum of HDPE were detected (Smith, 2021). In the case of the PS component, IR data were characterized by aromatic C-H stretching bands at 3057 and 3021 cm^{-1} , the asymmetric (2921 cm^{-1}) and symmetric (2853 cm^{-1}) CH₂ stretches and the vibration of the aromatic ring at 1491 cm^{-1} (Fang et al., 2010). In addition, the asymmetric (2918 cm^{-1}) and symmetric (2852 cm^{-1}) CH₂ stretches, C-Cl stretching band at 1729 cm^{-1} were observed in the IR spectrum of PVC (Bellamy, 1964; Campbell and Raucher 1955; Krimm et al., 1956; Stromberg et al., 1958). In the results of the study, dominant polymer types in the analyses show parallelism with the polymer types that are

intensive in production (Plastics Europe, 2022), and similar results were also reported by other researchers (Mülayim et al., 2022).

The Black Sea is particularly vulnerable to microplastic pollution. The coasts of the Black Sea, which are quite smooth, are disturbed by the protrusions formed by important headlands such as the Sinop Peninsula. The population density is low, and the city is remote from pollutant sources. The Sinop coast has been identified as a critical area due to its location and the presence of several sources of plastic pollution, such as tourism and fishing activities (Bat et al., 2022; Öztekin et al., 2020). The microplastic presence of the water column in the Hamsilos of the Black Sea can be attributed to various sources. One of the primary sources is likely the discharge of untreated or inadequately treated domestic and agricultural wastewater into the sea, which can carry microplastics and other pollutants. Other possible sources of plastic litter can be fishing and shipping activities. Although there is no industrial activity and no settlement in Hamsilos, unfortunately, microplastics can reach Hamsilos in various ways, for example, they can float on the surface of seawater because of their low density and be carried by surface currents. The movement of microplastics in seawater is influenced by various factors, such as sea currents, wind, and salinity (Browne et al., 2010; GESAMP, 2019; Kowalski et al., 2016). The size, shape, and density of the microplastics and biofouling also play a role in their movement (Kaiser et al., 2017; Liu et al., 2022). Additionally, the location of microplastic sources, such as wastewater discharge or coastal development, can affect their distribution in the sea. Some microplastics may also sink slightly below the surface of the water and be transported by subsurface currents. However, vertical mixing in Hamsilos can cause microplastics to be transported up or down in the water column, where they can be carried by currents. The arrival of plastics in the Black Sea from litter belonging to different countries to the shores of Türkiye (Bat et al., 2022; Öztekin et al., 2020) is concerning from an environmental and public health perspective. This occurrence highlights the need for improved waste management practices, both locally and internationally.

4 Conclusion

Microplastic pollution is an increasingly significant environmental issue that poses a threat to the health and integrity of marine ecosystems, as well as to human health. The Black Sea is particularly vulnerable to microplastic pollution due to the high levels of human activity and the heavy shipping traffic in the region (Bat & Öztekin, 2022; BSC, 2007). The Hamsilos region of the Sinop coast is an important ecological hotspot in the Black Sea, which hosts a diverse range of marine organisms (Üstün, 2019). The results of this investigation showed that the water column in the Hamsilos Bay was contaminated by microplastics in both all sampling stations and months. The most common microplastic shape in the water column was fibres, which likely originated from wastewater discharge. The synthetic polymers in the examined microplastic samples of this study were PET, PE, HDPE, PVC, and PS and the dominant polymer types in the analyses show parallelism with the polymer types that are intensive in production. Therefore, the study of microplastics in water column collected from this area can contribute to the literature on the evaluation of microplastic pollution in marine ecosystems.

Acknowledgements The authors thank Dr. Uğur Öz sandıkçı for his help on the map.

Author Contributions Ayşah Öztekin: Analysis, Data curation, Visualization, Writing—original draft and review & editing; Funda Üstün: Fieldwork, Funding acquisition, Writing—review & editing; Levent Bat: Writing—original draft and review & editing; Ahmet Tabak: FTIR analysis, Writing—review & editing.

All authors read and approved the final manuscript.

All authors involved in this research, interpretation of data and conclusions, assisted in drafting and revising the manuscript, and read and approved this submission.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The research was supported by Sinop University with Scientific Research Project; project number SÜF-1901–14-04.

Data Availability The datasets generated during and analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Consent to Participate Not applicable.

Consent for Publication All the authors agree to publish.

Competing Interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Akkan, E. (1975). *Sinop Yarımadasının Jeomorfolojisi*. Ankara Üniversitesi Dil ve Tarih Coğrafya Fakültesi Yayınları No:261. Turkish: Ankara University Publisher.
- Andrady, A. L. (2017). The plastic in microplastics: A review. *Marine Pollution Bulletin*, 119(1), 12–22. <https://doi.org/10.1016/j.marpolbul.2017.01.082>
- Aytan, U., Valente, A., Senturk, Y., Usta, R., Sahin, F. B. E., Mazlum, R. E., & Agirbas, E. (2016). First evaluation of neustonic microplastics in Black Sea waters. *Marine Environmental Research*, 119, 22–30. <https://doi.org/10.1016/j.marenvres.2016.05.009>
- Aytan, Ü., Şentürk, Y., Esensoy, F.B., Öztekin, A., Ağırbaş, E., & Valente, A. (2020). Microplastic pollution along the southeastern Black Sea. In Ü. Aytan, M. Pogojeva, & A. Simeonova, (Eds.), *Marine Litter in the Black Sea* (pp. 192). Turkish Marine Research Foundation (TUDAV), 56, Istanbul, Turkey.
- Aytan, U., Esensoy, F. B., & Senturk, Y. (2022). Microplastic ingestion and egestion by copepods in the Black Sea. *Science of the Total Environment*, 806, 150921. <https://doi.org/10.1016/j.scitotenv.2021.150921>
- Aliabad, M. K., Nassiri, M., & Kor, K. (2019). Microplastics in the surface seawaters of Chabahar Bay, Gulf of Oman (Makran coasts). *Marine Pollution Bulletin*, 143, 125–133. <https://doi.org/10.1016/j.marpolbul.2019.04.037>
- Bat, L., & Gökkurt Baki, O. (2014). Seasonal variations of sediment and water quality correlated to land-based pollution sources in the middle of the Black Sea coast. *Turkey. International Journal of Marine Science*, 4(12), 108–118. <https://doi.org/10.5376/ijms.2014.04.0012>
- Bat, L., Öztekin, A., Şahin, F., Arıcı, E., & Öz sandıkçı, U. (2018). An overview of the Black Sea pollution in Turkey. *Mediterranean Fisheries and Aquaculture Research*, 1(2), 66–86.
- Bat, L., Öztekin, A., Öztürk, D. K., Gürbüz, P., Öz sandıkçı, U., Eyüboğlu, B., & Öztekin, H. C. (2022). Beach litter contamination of the Turkish middle Black Sea coasts: Spatial and temporal variation, composition, and possible sources. *Marine Pollution Bulletin*, 185, 114248. <https://doi.org/10.1016/j.marpolbul.2022.114248>
- Bat, L., & Öztekin, A. (2022). Microplastic Pollution in the Black Sea: an overview of the current situation. In: M. Hashmi. (Eds.), *Microplastic Pollution. Emerging Contaminants and Associated Treatment Technologies*. Springer, Cham. https://doi.org/10.1007/978-3-030-89220-3_8
- Bellamy, L. J. (1964). *The infra-red spectra of complex molecules*. Springer Science & Business Media, No. 544.6, B45.
- Berov, D., & Klayn, S. (2020). Microplastics and floating litter pollution in Bulgarian Black Sea coastal waters. *Marine Pollution Bulletin*, 156, 111225. <https://doi.org/10.1016/j.marpolbul.2020.111225>
- Browne, M. A., Galloway, T. S., & Thompson, R. C. (2010). Spatial patterns of plastic debris along estuarine shorelines. *Environmental Science & Technology*, 44(9), 3404–3409. <https://doi.org/10.1021/es903784e>
- Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: Sources and sinks. *Environmental Science & Technology*, 45(21), 9175–9179. <https://doi.org/10.1021/es201811s>
- Boucher, J., & Friot, D. (2017). *Primary Microplastics in the Oceans: A Global Evaluation of Sources* (p. 43). IUCN.
- BSC, (2007). *Marine Litter in the Black Sea Region: a Review of the Problem*, Black Sea Commission Publications 2007–1, Istanbul, Turkey, (pp. 160).
- Carpenter, E. J., & Smith, K. L., Jr. (1972). Plastics on the Sargasso Sea surface. *Science*, 175(4027), 1240–1241. <https://doi.org/10.1126/science.175.4027.1240>
- Campbell, J. E., & Rauscher, W. H. (1955). Base accelerated degradation of polyvinyl chloride. *Journal of Polymer Science*, 18(90), 461–478.
- Carlin, J., Craig, C., Little, S., Donnelly, M., Fox, D., Zhai, L., & Walters, L. (2020). Microplastic accumulation in the gastrointestinal tracts in birds of prey in central Florida, USA. *Environmental Pollution*, 264, 114633. <https://doi.org/10.1016/j.envpol.2020.114633>
- Chen, Z., Hay, J. N., & Jenkins, M. J. (2013). The thermal analysis of poly (ethylene terephthalate) by FTIR spectroscopy. *Thermochimica Acta*, 552, 123–130. <https://doi.org/10.1016/j.tca.2012.11.002>
- Cincinelli, A., Martellini, T., Guerranti, C., Scopetani, C., Chelazzi, D., & Giarrizzo, T. (2019). A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea. *TrAC Trends in Analytical Chemistry*, 110, 321–326. <https://doi.org/10.1016/j.trac.2018.10.026>

- Dai, Z., Zhang, H., Zhou, Q., Tian, Y., Chen, T., Tu, C., ... & Luo, Y. (2018). Occurrence of microplastics in the water column and sediment in an inland sea affected by intensive anthropogenic activities. *Environmental pollution*, 242, 1557–1565. <https://doi.org/10.1016/j.envpol.2018.07.131>
- De La Fuente, R., Drótos, G., Hernández-García, E., López, C., & Van Sebille, E. (2021). Sinking microplastics in the water column: Simulations in the Mediterranean Sea. *Ocean Science*, 17(2), 431–453. <https://doi.org/10.5194/os-17-431-2021>
- Dekiff, J. H., Remy, D., Klasmeyer, J., & Fries, E. (2014). Occurrence and spatial distribution of microplastics in sediments from Norderney. *Environmental Pollution*, 186, 248–256. <https://doi.org/10.1016/j.envpol.2013.11.019>
- Desforges, J. P. W., Galbraith, M., & Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology*, 69, 320–330. <https://doi.org/10.1007/s00244-015-0172-5>
- Dris, R., Imhof, H. K., Löder, M. G., Gasperi, J., Laforsch, C., & Tassin, B. (2018). Microplastic contamination in freshwater systems: Methodological challenges, occurrence and sources. In *Microplastic Contamination in Aquatic Environments* (pp. 51–93). Elsevier. <https://doi.org/10.1016/B978-0-12-813747-5.00003-5>
- Edge, M., Wiles, R., Allen, N. S., McDonald, W. A., & Mortlock, S. V. (1996). Characterisation of the species responsible for yellowing in melt degraded aromatic polyesters—I: Yellowing of poly (ethylene terephthalate). *Polymer Degradation and Stability*, 53(2), 141–151. [https://doi.org/10.1016/0141-3910\(96\)00081-X](https://doi.org/10.1016/0141-3910(96)00081-X)
- Eo, S., Hong, S. H., Song, Y. K., Han, G. M., & Shim, W. J. (2019). Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. *Water Research*, 160, 228–237. <https://doi.org/10.1016/j.watres.2019.05.053>
- Eryaşar, A. R., Gedik, K., Şahin, A., Öztürk, R. Ç., & Yılmaz, F. (2021). Characteristics and temporal trends of microplastics in the coastal area in the Southern Black Sea over the past decade. *Marine Pollution Bulletin*, 173, 112993. <https://doi.org/10.1016/j.marpolbul.2021.112993>
- Eryaşar, A. R., Gedik, K., & Mutlu, T. (2022). Ingestion of microplastics by commercial fish species from the southern Black Sea coast. *Marine Pollution Bulletin*, 177, 113535. <https://doi.org/10.1016/j.marpolbul.2022.113535>
- Fang, J., Xuan, Y., & Li, Q. (2010). Preparation of polystyrene spheres in different particle sizes and assembly of the PS colloidal crystals. *Science China Technological Sciences*, 53, 3088–3093. <https://doi.org/10.1007/s11431-010-4110-5>
- Frias, J. P., & Nash, R. (2019). Microplastics: Finding a consensus on the definition. *Marine Pollution Bulletin*, 138, 145–147. <https://doi.org/10.1016/j.marpolbul.2018.11.022>
- Gulmine, J. V., Janissek, P. R., Heise, H. M., & Akcelrud, L. (2002). Polyethylene Characterization by FTIR. *Polymer Testing*, 21(5), 557–563. [https://doi.org/10.1016/S0142-9418\(01\)00124-6](https://doi.org/10.1016/S0142-9418(01)00124-6)
- Güven, O. (2022). Spatio-temporal distribution and characterization of microplastic pollution in the three main freshwater systems (Aksu and Köprü Streams, Manavgat River) and fishing grounds located in their vicinities in the Antalya Bay. *Turkish Journal of Fisheries and Aquatic Sciences*, 22(7). <https://doi.org/10.4194/TRJFA S20507>
- Hanke, G., Galgani, F., Werner, S., Oosterbaan, L., Nilsson, P., Fleet, D., ... & Liebbezeit, G. (2013). *Guidance on monitoring of marine litter in European Seas* EUR 26113. Publications Office of the European Union. JRC83985. <https://doi.org/10.2788/99816>
- Haslam, J., Willis, H. A., & Squirrel, D. C. M. (1983). *Identification and Analysis of Plastics* (2nd ed., p. 748), Wiley.
- Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology*, 46(6), 3060–3075. <https://doi.org/10.1021/es2031505>
- Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment*, 586, 127–141. <https://doi.org/10.1016/j.scitotenv.2017.01.190>
- Irfan, M., Qadir, A., Mumtaz, M., & Ahmad, S. R. (2020). An unintended challenge of microplastic pollution in the urban surface water system of Lahore. *Pakistan Environmental Science and Pollution Research*, 27(14), 16718–16730. <https://doi.org/10.1007/s11356-020-08114-7>
- GESAMP (2019). *Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean* (Kershaw P.J., Turra A. and Galgani F. Eds.), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 99, (p. 130).
- Ivar do Sul, J. A. L., Costa, M. F., Barletta, M., & Cysneiros, F. J. A. (2013). Pelagic microplastics around an archipelago of the Equatorial Atlantic. *Marine pollution bulletin*, 75(1-2), 305-309. <https://doi.org/10.1016/j.marpolbul.2013.07.040>
- Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, 347(6223), 768–771. <https://doi.org/10.1126/science.1260352>
- Jeong, C. B., Won, E. J., Kang, H. M., Lee, M. C., Hwang, D. S., Hwang, U. K., ... & Lee, J. S. (2016). Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the monogonont rotifer (*Brachionus koreanus*). *Environmental science & technology*, 50(16), 8849–8857. <https://doi.org/10.1021/acs.est.6b01441>
- Kama, N. A., Rahim, S. W., & Yaşin, K. (2021). Microplastic concentration in column seawater compartment in Burau, Luwu Regency, South Sulawesi, Indonesia. In *IOP Conference Series: Earth and Environmental Science*, 763(1), 012061. IOP Publishing. <https://doi.org/10.1088/1755-1315/763/1/012061>
- Kaiser, D., Kowalski, N., & Waniek, J. J. (2017). Effects of biofouling on the sinking behavior of microplastics. *Environmental Research Letters*, 12(12), 124003. <https://doi.org/10.1088/1748-9326/aa8e8b>
- Kang, H. J., Park, H. J., Kwon, O. K., Lee, W. S., Jeong, D. H., Ju, B. K., & Kwon, J. H. (2018). Occurrence of

- microplastics in municipal sewage treatment plants: A review. *Environ. Health. Toxicol.*, 33, e2018013–e2018010. <https://doi.org/10.5620/eht.e2018013>
- Karami, A., Golieskardi, A., Choo, C. K., Romano, N., Ho, Y. B., & Salamatinia, B. (2017). A high-performance protocol for extraction of microplastics in fish. *Science of the Total Environment*, 578, 485–494. <https://doi.org/10.1016/j.scitotenv.2016.10.213>
- Kowalski, N., Reichardt, A. M., & Waniek, J. J. (2016). Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors. *Marine Pollution Bulletin*, 109(1), 310–319.
- Krimm, S., Liang, C. Y., & Sutherland, G. B. B. M. (1956). Infrared spectra of high polymers. V. Polyvinyl alcohol. *Journal of Polymer Science*, 22(101), 227–247.
- Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D. W., & Law, K. L. (2012). The effect of wind mixing on the vertical distribution of buoyant plastic debris. *Geophysical research letters*, 39(7). <https://doi.org/10.1029/2012GL051116>
- Liedermann, M., Gmeiner, P., Pessenlehner, S., Haimann, M., Hohenblum, P., & Habersack, H. (2018). A methodology for measuring microplastic transport in large or medium rivers. *Water*, 10(4), 414. <https://doi.org/10.3390/w10040414>
- Liu, S., Huang, Y., Luo, D., Wang, X., Wang, Z., Ji, X., ... & Shang, X. (2022). Integrated effects of polymer type, size and shape on the sinking dynamics of biofouled microplastics. *Water Research*, 220, 118656. <https://doi.org/10.1016/j.watres.2022.118656>
- Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., & Soudant, P. (2015). Interactions between microplastics and phytoplankton aggregates: Impact on their respective fates. *Marine Chemistry*, 175, 39–46. <https://doi.org/10.1016/j.marchem.2015.04.003>
- Lusher, A. L., Tirelli, V., O'Connor, I., & Officer, R. (2015). Microplastics in Arctic polar waters: The first reported values of particles in surface and sub-surface samples. *Scientific Reports*, 5(1), 14947. <https://doi.org/10.1038/srep14947>
- MAF, (2023). Ministry of Agriculture and Forestry, Sinop-Hamsilos Natural Park. Retrieved March 3, 2023, from <https://bolge10.tarimorman.gov.tr/Menu/48/Sinop-Hamsilos-Tabiat-Parki> (in Turkish).
- Masura, J., Baker, J., Foster, G., & Arthur, C. (2015). *Laboratory methods for the analysis of microplastics in the marine environment: Recommendations for quantifying synthetic particles in waters and sediments* (p. 39). NOAA Technical Memorandum NOS-OR&R-48. <https://repository.library.noaa.gov/view/noaa/10296>
- Mukhanov, V. S., Litvinyuk, D. A., Sakhon, E. G., Bagaev, A. V., Veerasingam, S., & Venkatachalapathy, R. (2019). A new method for analyzing microplastic particle size distribution in marine environmental samples. *Ecologica Montenegrina*, 23, 77–86. <https://doi.org/10.37828/em.2019.23.10>
- Mülâyim, A., Bat, L., Öztekin, A., Gündüz, S. K., Yücedağ, E., & Bıçak, B. (2022). Microplastic Accumulation in Crayfish *Astacus leptodactylus* (Eschscholtz 1823) and Sediments of Durusu (Terkos) Lake (Turkey). *Water, Air, & Soil Pollution*, 233(11), 449. <https://doi.org/10.1007/s11270-022-05908-y>
- Nelms, S. E., Barnett, J., Brownlow, A., Davison, N. J., Deaville, R., Galloway, T. S., ... & Godley, B. J. (2019). Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory?. *Scientific Reports*, 9(1), 1075. <https://doi.org/10.1038/s41598-018-37428-3>
- Nizzetto, L., Bussi, G., Futter, M. N., Butterfield, D., & Whitehead, P. G. (2016). A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. *Environmental Science: Processes & Impacts*, 18(8), 1050–1059. <https://doi.org/10.1039/c6em00206d>
- Nuelle, M. T., Dekiff, J. H., Remy, D., & Fries, E. (2014). A new analytical approach for monitoring microplastics in marine sediments. *Environmental Pollution*, 184, 161–169. <https://doi.org/10.1016/j.envpol.2013.07.027>
- Ogonowski, M., Schür, C., Jarsén, Å., & Gorokhova, E. (2016). The effects of natural and anthropogenic microparticles on individual fitness in *Daphnia magna*. *PLoS ONE*, 11(5), e0155063. <https://doi.org/10.1371/journal.pone.0155063>
- Ory, N. C., Sobral, P., Ferreira, J. L., & Thiel, M. (2017). Amberstripe scad *Decapterus muroadsi* (Carangidae) fish ingest blue microplastics resembling their copepod prey along the coast of Rapa Nui (Easter Island) in the South Pacific subtropical gyre. *Science of the Total Environment*, 586, 430–437.
- Öztekin, A., & Bat, L. (2017). Microlitter pollution in sea water: A preliminary study from Sinop Sarikum coast of the southern Black Sea. *Journal of Fisheries and Aquatic Sciences*, 17, 1431–1440. https://doi.org/10.4194/1303-2712-v17_6_37
- Oztekin, A., & Bat, L. (2020). Marine litter problem in the southern Black Sea coastal area: An overview of the big pressure in Sinop. *Marine litter in the Black Sea*, 56, 82–93.
- Öztekin, A., Bat, L., & Gökkurt-Baki, O. (2020). Beach litter pollution in Sinop Sarikum Lagoon coast of the southern Black Sea. *Journal of Fisheries and Aquatic Sciences*, 20(3), 197–205. https://doi.org/10.4194/1303-2712-v20_3_04
- Pereira, A. P. D. S., Silva, M. H. P. D., Lima, É. P., Paula, A. D. S., & Tommasini, F. J. (2017). Processing and characterization of PET composites reinforced with geopolymer concrete waste. *Materials Research*, 20, 411–420. <https://doi.org/10.1590/1980-5373-MR-2017-0734>
- Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., & Li, D. (2017). Microplastics in sediments of the Changjiang Estuary, China. *Environmental Pollution*, 225, 283–290. <https://doi.org/10.1016/j.envpol.2016.12.064>
- Piazzolla, D., Bonamano, S., De Muto, F., Scanu, S., Bernardini, S., Sodo, A., ... & Marcelli, M. (2023). Micro-litter occurrence, distribution, and summertime transport trajectories in the coastal waters of the north-eastern Tyrrhenian Sea (Italy). *Geosystems and Geoenvironment*, 100192. <https://doi.org/10.1016/j.geogeo.2023.100192>
- Plastics Europe, (2022). *Plastics—The facts 2022*. Plastic Europe. (https://plasticseurope.org/wp-content/uploads/2022/10/PE-PLASTICS-THE-FACTS_V7-Tue_19-10-1.pdf)
- Pojar, I., Kochleus, C., Dierkes, G., Ehlers, S. M., Reifferscheid, G., & Stock, F. (2021). Quantitative and qualitative evaluation of plastic particles in surface waters of the Western Black Sea. *Environmental Pollution*, 268, 115724. <https://doi.org/10.1016/j.envpol.2020.115724>

- Reisser, J., Slat, B., Noble, K., Du Plessis, K., Epp, M., Proietti, M., ... & Pattiaratchi, C. (2015). The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic Gyre. *Biogeosciences*, *12*(4), 1249–1256. <https://doi.org/10.5194/bg-12-1249-2015>
- Rodríguez-Seijo, A., & Pereira, R. (2017). Morphological and physical characterization of microplastics. *Comprehensive Analytical Chemistry*, *75*, 49–66.
- Rodrigues, S. M., Elliott, M., Almeida, C. M. R., & Ramos, S. (2021). Microplastics and plankton: Knowledge from laboratory and field studies to distinguish contamination from pollution. *Journal of Hazardous Materials*, *417*, 126057. <https://doi.org/10.1016/j.jhazmat.2021.126057>
- Ryan, P. G., Moore, C. J., Van Franeker, J. A., & Moloney, C. L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society b: Biological Sciences*, *364*(1526), 1999–2012. <https://doi.org/10.1098/rstb.2008.0207>
- Sadri, S. S., & Thompson, R. C. (2014). On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary. *Southwest England. Marine Pollution Bulletin*, *81*(1), 55–60. <https://doi.org/10.1016/j.marpolbul.2014.02.020>
- Shaw, D. G., & Day, R. H. (1994). Colour and form-dependent loss of plastic micro-debris from the North Pacific Ocean. *Marine Pollution Bulletin*, *28*(1), 39–43. [https://doi.org/10.1016/0025-326X\(94\)90184-8](https://doi.org/10.1016/0025-326X(94)90184-8)
- Siegfried, M., Koelmans, A. A., Besseling, E., & Kroeze, C. (2017). Export of microplastics from land to sea. A Modelling Approach. *Water Research*, *127*, 249–257. <https://doi.org/10.1016/j.watres.2017.10.011>
- Silverstein, R. M., & Webster, F. X. (1998). 13C NMR spectrometry. *Spectrometric identification of organic compounds* (pp. 217–249).
- Smith, B. (2021). The infrared spectra of polymers II: polyethylene. *Spectroscopy*, *36*(9), 24–29. <https://doi.org/10.56530/spectroscopy.xp7081p7>
- Stromberg, R. R., Straus, S., & Achhammer, B. G. (1958). Infrared spectra of thermally degraded poly (vinyl chloride). *Journal of Research of the National Bureau of Standards*, *60*(2), 147–152.
- Svetlichny, L., Isinibilir, M., Mykitchak, T., Eryalçın, K. M., Türkeri, E. E., Yuksel, E., & Kideys, A. E. (2021). Microplastic consumption and physiological response in *Acartia clausi* and *Centropages typicus*: Possible roles of feeding mechanisms. *Regional Studies in Marine Science*, *43*, 101650. <https://doi.org/10.1016/j.rsma.2021.101650>
- Terzi, Y., Gedik, K., Eryaşar, A. R., Öztürk, R. Ç., Şahin, A., & Yılmaz, F. (2022). Microplastic contamination and characteristics spatially vary in the southern Black Sea beach sediment and sea surface water. *Marine Pollution Bulletin*, *174*, 113228. <https://doi.org/10.1016/j.marpolbul.2021.113228>
- Teuten, E. L., Rowland, S. J., Galloway, T. S., & Thompson, R. C. (2007). Potential for plastics to transport hydrophobic contaminants. *Environmental Science & Technology*, *41*(22), 7759–7764. <https://doi.org/10.1021/es071737s>
- Üstün, F. (2019). Seasonal cycle of zooplankton abundance and biomass in Hamsilos Bay, Sinop, Southern Black Sea, Turkey. *Journal of Natural History*, *53*(7–8), 365–389. <https://doi.org/10.1080/00222933.2019.1592257>
- Üstün, F., & Birinci Özdemir, Z. (2019). Seasonal distribution of gelatinous macrozooplankton in the Hamsilos Bay, southern Black Sea, Turkey. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi*, *22*(4), 583–592. <https://doi.org/10.18016/ksutarimdogu.vi.511807>
- Van Cauwenberghe, L., Vanreusel, A., Mees, J., & Janssen, C. R. (2013). Microplastic pollution in deep-sea sediments. *Environmental Pollution*, *182*, 495–499. <https://doi.org/10.1016/j.envpol.2013.08.013>
- Wang, W., Ndungu, A. W., Li, Z., & Wang, J. (2017). Microplastics pollution in inland freshwaters of China: A case study in urban surface waters of Wuhan, China. *Science of the Total Environment*, *575*, 1369–1374.
- Wang, W., Yuan, W., Chen, Y., & Wang, J. (2018). Microplastics in surface waters of Dongting lake and hong lake, China. *Science of the Total Environment*, *633*, 539–545. <https://doi.org/10.1016/j.scitotenv.2018.03.211>
- Wang, X., Zhu, L., Liu, K., & Li, D. (2022). Prevalence of microplastic fibres in the marginal sea water column off southeast China. *Science of the Total Environment*, *804*, 150138. <https://doi.org/10.1016/j.scitotenv.2021.150138>
- Wessel, C. C., Lockridge, G. R., Battiste, D., & Cebrian, J. (2016). Abundance and characteristics of microplastics in beach sediments: Insights into microplastic accumulation in northern Gulf of Mexico estuaries. *Marine Pollution Bulletin*, *109*(1), 178–183. <https://doi.org/10.1016/j.marpolbul.2016.06.002>
- Woodall, L. C., Sanchez-Vidal, A., Canals, M., Paterson, G. L., Coppock, R., Sleight, V., ... & Thompson, R. C. (2014). The deep sea is a major sink for microplastic debris. *Royal Society open science*, *1*(4), 140317. <https://doi.org/10.1098/rsos.140317>
- Wright, L. S., Napper, I. E., & Thompson, R. C. (2021). Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density. *Marine Pollution Bulletin*, *173*, 113115. <https://doi.org/10.1016/j.marpolbul.2021.113115>
- Xu, X., Wong, C. Y., Tam, N. F., Lo, H. S., & Cheung, S. G. (2020). Microplastics in invertebrates on soft shores in Hong Kong: Influence of habitat, taxa and feeding mode. *Science of the Total Environment*, *715*, 136999. <https://doi.org/10.1016/j.scitotenv.2020.136999>
- Xue, B., Zhang, L., Li, R., Wang, Y., Guo, J., Yu, K., & Wang, S. (2020). Underestimated microplastic pollution derived from fishery activities and “hidden” in deep sediment. *Environmental Science & Technology*, *54*(4), 2210–2217. <https://doi.org/10.1021/acs.est.9b04850>
- Xiong, X., Zhang, K., Chen, X., Shi, H., Luo, Z., & Wu, C. (2018). Sources and distribution of microplastics in China's largest inland lake—Qinghai Lake. *Environmental Pollution*, *235*, 899–906. <https://doi.org/10.1016/j.envpol.2017.12.081>
- Yang, L., Zhang, Y., Kang, S., Wang, Z., & Wu, C. (2021). Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Science of the Total Environment*, *754*, 141948. <https://doi.org/10.1016/j.scitotenv.2020.141948>
- Yu, Z., Peng, B., Liu, L. Y., Wong, C. S., & Zeng, E. Y. (2019). Development and validation of an efficient method for processing microplastics in biota samples.

- Environmental Toxicology and Chemistry*, 38(7), 1400–1408. <https://doi.org/10.1002/etc.4416>
- Zhang, H. (2017). Transport of microplastics in coastal seas. *Estuarine, Coastal and Shelf Science*, 199, 74–86. <https://doi.org/10.1016/j.ecss.2017.09.032>
- Zhu, L., Wang, H., Chen, B., Sun, X., Qu, K., & Xia, B. (2019). Microplastic ingestion in deep-sea fish from the South China Sea. *Science of the Total Environment*, 677, 493–501. <https://doi.org/10.1016/j.scitotenv.2019.04.380>
- Zbinden, R. (1964). *Infrared spectroscopy of high polymers* (p. 263). Academic Press.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.