



Microplastic pollution and ecological risk assessment of a pond ecosystem

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Abstract Microplastic (MP) pollution has been observed in various ecosystems as a result of the rapid increase in plastic production over the past half-century. Nevertheless, the extent of MP pollution in different ecosystems, particularly in freshwater ecosystems, has not been well-studied, and there are limited investigations on this particular topic, specifically in Türkiye. Here, we quantify the occurrence and distribution of MPs in surface water samples collected from Topçu Pond (Türkiye) for the first time. Water samples were collected at five stations and filtered (30 L for each station) through stacked stainless steel sieves (5 mm, 328 µm, and 61 µm mesh size) with a diameter of 30 cm. The abundance, size, color, shape, and type of collected debris samples were analyzed after the wet peroxide oxidation process. MP particles were observed in all samples at an average abundance of 2.4 MPs/L. The most abundant MP size class and type were 0–999 µm and fiber respectively. On the other hand, prevalent colors were black and colorless in general. According to the Raman analysis results, the identified MP derivatives were polypropylene (40%), polyamide (30%), ethylene acrylic acid (20%),

and polyvinylchloride (10%). Moreover, the pollution load index (PLI) index was used to determine the pollution status. PLI values were determined as 1.91 at station S1, 1.73 at station S2, 1.31 at station S3, 1 at station S4 and 1.24 at station S5. The PLI value determined for the overall pond was 1.4. The results of this research show that MP pollution is present in Topçu Pond and contributes to the expanding literature on MP pollution in pond ecosystems.

Keywords Microplastic · Plastic · Pond · Waste · Pollution · Index · Türkiye

Introduction

Plastic pollution has become a global problem, especially in recent decades. Considering the tools made of plastic materials used in daily life, it seems almost impossible to remove plastic from our lives (Bhat, 2024; Citterich et al., 2023; Earn et al., 2021). The main reasons for the widespread use of plastic materials can be listed as follows: they are cheap in cost, durable, and easy to shape and color (Heller et al., 2020). Other factors that contribute to the increase in the production of plastic materials include population growth and consumption-oriented lifestyles (Kurniawan et al., 2023). As long as people's consumption-oriented lifestyle does not change and plastic material is not replaced by more environmentally friendly materials, plastic pollution will continue to increase

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in the coming years (Lau et al., 2020; Mangal et al., 2023; Patrício Silva et al., 2020; Thacharodi et al., 2024).

Plastic materials vary in size, shape, color, and polymeric properties depending on the purpose of the production. Although they are generally produced in large sizes, when they are left to nature, they are exposed to environmental factors such as sunlight and break up into small pieces over time. Among these plastic particles, those with a size of less than 5 mm are defined as microplastics (MPs) (Blettler et al., 2017; Van Cauwenberghe et al., 2015). In today's world, the recycling rate of plastic waste is unfortunately very low, many countries use ways to get rid of plastic waste by selling their plastic waste to other countries or leaving it to terrestrial or aquatic ecosystems (Joshi et al., 2020; Liang et al., 2021; Wen et al., 2021; C. Zhao et al., 2021). However, it is obvious that these methods do not provide a solution; plastics are transported from one country to another or from one ecosystem to another ecosystem. (Horejs, 2020).

Pond ecosystems are important in preventing the loss of biodiversity by creating habitats, flood control, and groundwater recharging (Bartrons et al., 2024; Biggs et al., 2016; Chaudhari & Samnani, 2023). At the same time, ponds are also described as stepping stones in preventing the decrease in species dispersal, which is one of the consequences of habitat loss due to increasing urbanization and global climate change (Cuenca-Cambronero et al., 2023). In addition to these benefits, they are also important for human well-being, e.g., for agricultural irrigation, flood mitigation, or fish farming (there was a fish farm in Topcu Pond, which is not active today) (Biggs et al., 2016). MP pollution in pond ecosystems can adversely affect the biodiversity found in the system. It can also be transferred to humans via contaminated organisms consumed as food (Hossain et al., 2023). On the other hand, the use of pond water as irrigation water for agriculture can lead to the transfer of MPs to terrestrial ecosystems (Jiang et al., 2023).

While many studies in recent years have contributed to our understanding of the extent of plastic pollution in different ecosystems, the number of detailed research efforts on freshwater ecosystems is still relatively limited, especially in Türkiye (Mutlu et al., 2024; Yabancı et al., 2019). Freshwater ecosystems are essential for the survival of many species,

including humans, but they are also ecosystems that are heavily affected by human impact (Amoatey & Baawain, 2019; Bhat & Janaszek, 2024). It has been determined by many studies that the freshwater ecosystems located geographically close to recreational areas, industrial establishments, and areas with high urbanization are exposed to human influence (Prunier et al., 2018; Stone et al., 2020). Although eutrophication is the most striking of these effects to date, plastic pollution can be defined as a relatively new type of pollution (Bharath et al., 2021). For this reason, determining the extent and sources of plastic pollution in freshwater ecosystems is crucial for anticipating future issues and implementing preventive measures. In this study, MP pollution levels were determined by analyzing water samples from five stations in Topçu Pond. This study is one of our aims to investigate the presence and abundance of MP pollution in the Topçu Pond. The first time MP pollution was studied in the selected pond, and it was also aimed at contributing to public awareness of MP pollution in pond ecosystems in general.

Materials and methods

Study site and sampling

Topçu Pond is located in the north of Yozgat Province, about 9 km from the city center. The pond's area is 13 ha, and its altitude is 1207 m. The pond's basin is mainly covered by agricultural land and the pond's water is mainly used for irrigation. The main inflows of the pond are Karacaoğlan and Zaptiye (seasonal) streams (Akgöz & Güler 2004). There is a fish production facility that was previously established in the pond, but this facility has not been active in recent years, only angling is allowed in the pond. It is also known that fish stocks, especially carp juveniles, are released into the pond by ministry officials.

Water samples were collected from five sampling sites via steel bucket (Fig. 1) and were filtered (30 L for each station) through stacked stainless steel sieves (5 mm, 328 μ m, and 61 μ m pore size) with a diameter of 30 cm. The particles remaining on the sieves were cleaned with pre-filtered distilled water and poured into sample bottles. Samples were collected as five replicates.

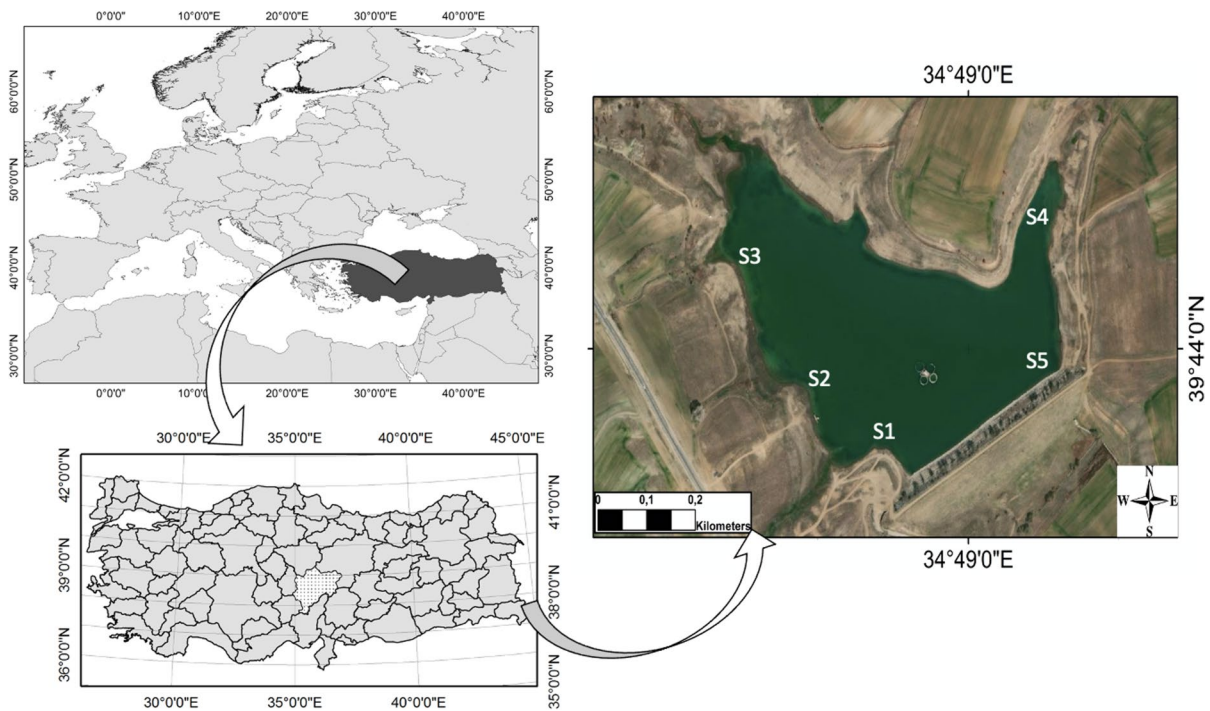


Fig. 1 Topçu Pond location and sampling sites

Sample preparation and examination

The samples brought to the laboratory were poured into beakers and each sample container was rinsed three times with distilled water to remove the remaining particles. MP separation was carried out according to the NOAA method (Masura et al., 2015). The beakers were covered with aluminum foil and dried in an oven at 75 °C until the water evaporated completely. Subsequently, wet-peroxidation was carried out to remove the organic material that may be present in the samples. During this process, 20 ml of 0.05 M Fe solution and 20 ml of hydrogen peroxide (30%) were poured into each beaker to eliminate the organic matter. After adding a stirrer to each beaker, they were covered with a watch glass and heated on the hot plate until bubbling was observed. As soon as bubbles were observed, the beaker was removed from the hot plate and placed back when the bubbling was over. When the bubbling was completely finished, hydrogen peroxide was re-added and this process was repeated until there was no more bubbling and no organic matter was visible in the solution. Then NaCl was then added to increase the density (1.2 g cm^{-3})

of the solution. After this process was performed for all beakers, the solutions were poured into separatory funnels and left to settle for 24 h. The settled particles were separated by opening the funnel tap. It was checked whether there were MPs in this separated part and if MPs were seen, they were separated. The remaining solution was filtered through filter papers with a pore size of 20 μm and each filter was placed in Petri dishes, dried, and examined under a stereo microscope (Olympus SZ61) (40 \times magnification). The size, color, and shape of the MPs were recorded during microscope counting.

Quality control

Prevention of contamination during work is a crucial stage, so a number of contamination prevention measures have been put in place during laboratory work (Bhat et al., 2024). All laboratory surfaces were cleaned with 70% ethanol, before starting the experiments and the laboratory was not used by other people during the studies. The use of materials containing plastic has been avoided as much as possible, and laboratory coats and nitrile gloves have been used

throughout the work. The hydrogen peroxide treatment stages in the study were carried out in a laminar cabinet. Unfortunately, it was not possible to use a laminar cabinet during the microscope counts. During all procedures, previously cleaned and examined Petri dishes were placed in close proximity to the study area and examined again under a stereo-microscope just after each stage of laboratory work. This process was repeated with new petri dishes at each stage. If contamination was detected, the determined number of MPs was excluded from the total count.

Verification of microplastic particles

Selected particles were also analyzed by Renishaw via confocal Raman microscope in the 4000–100 cm^{-1} range with 0.57 cm^{-1} resolution. Particles were examined under a Leica DM2500 microscope equipped with 5 \times , 20 \times , and 50 \times objectives. A diode laser excitation source was used at 785 nm and equipped with 1200 grooves/mm grating. The laser power was varied in the range of 2.3–230 mW depending on the type of sample. Raman spectra of samples were uploaded to the free online database Open Specy (Cowger et al., 2021) and pre-processed by smoothing (Savitzky–Golay filter (Savitzky & Golay, 1964)) and baseline correction techniques (IModPolyFit (J. Zhao et al., 2007)). The processed spectra of each particle were then identified using an on-board reference library, correlation-based matching criteria, and manual analysis of the spectra. The matching results were given by the open-source software along with the Pearson correlation coefficient used directly as the hit quality index. Pearson correlation coefficient values are ranked between 0 (lowest similarity) and 1 (highest similarity) and only values equal to or greater than 0.7 were considered satisfactory (Cowger et al., 2021).

Nile red (NR) ((N3013-Sigma) was also used to verify fiber particles. The particles were stained with 1 mL of NR solution (10 $\mu\text{g mL}^{-1}$ in acetone); after 15 min, the filters were rinsed thoroughly with Milli-Q water and vacuum-filtered to remove the accumulated liquid. Samples were dried and examined under a fluorescence microscope (Leica DM-4000).

Hot needle test was also utilized to differentiate plastic from non-plastic particles during counting, a method common in various studies (Bos et al., 2023; Wright et al., 2023). Fiber particle assessment criteria include no cell structure, consistent width, uniform

coloration, absence of segmented structures, and particles not shining (Nor & Obbard, 2014).

Ecological risk assessment of MP pollution

The pollution load index (PLI) is frequently used to determine the level of pollution in aquatic ecosystems (Tomlinson et al., 1980 Gong et al., 2023; Gosavi & Phuge, 2023). PLI value was calculated according to Eqs. (1) and (2), where C_i is the abundance of MPs and C_b is the background abundance of MPs value. Since no previous study on MP pollution has been conducted in the pond, the lowest amount of MPs determined in this study was used as the background value. A PLI value > 1 indicates the presence of MP pollution in the environment, while a value < 1 indicates that there is no MP pollution.

$$CF_i = \frac{C_i}{C_b} \quad (1)$$

$$PLI = \sqrt{CF_i} \quad (2)$$

$$PLI_{\text{pond}} = [CF_1 \times CF_2 \times CF_3 \cdots \times CF_n]^{1/n}$$

Statistical analysis

MP number differences among sampling stations were determined by one-way analysis of variance (ANOVA) followed by Tukey's HSD test (homogeneous variances). Normality was assessed by the Shapiro–Wilk test, and homogeneity of variances was checked by Levene's test. The values were considered to be significant when $p < 0.05$. All the statistical tests were conducted using R 4.0.2 software.

Result and discussion

Microplastic quantification

MP particles were observed in all stations and differences among stations were statistically significant according to one-way ANOVA result ($p < 0.01$). The highest and lowest MP numbers were observed at S1 (4 ± 1.4 MPs/L) and S4 (1.1 ± 0.1 MPs/L) stations, respectively. Average MP numbers for S2, S3, and S5

were 3.3 ± 1.5 , 1.9 ± 1.1 , and 1.7 ± 0.7 MPs/L, respectively (Fig. 2). Unlike the S4 and S5 stations, the S1, S2, and S3 stations are located on a flat land and close to the highway; therefore, local people generally prefer this area for recreation and fishing activities. In support of this idea, plastic wastes like plastic bottles

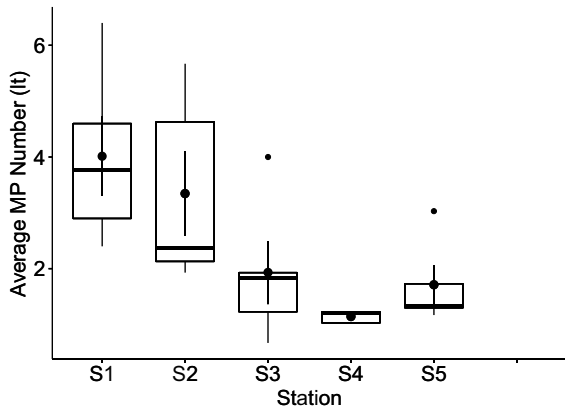
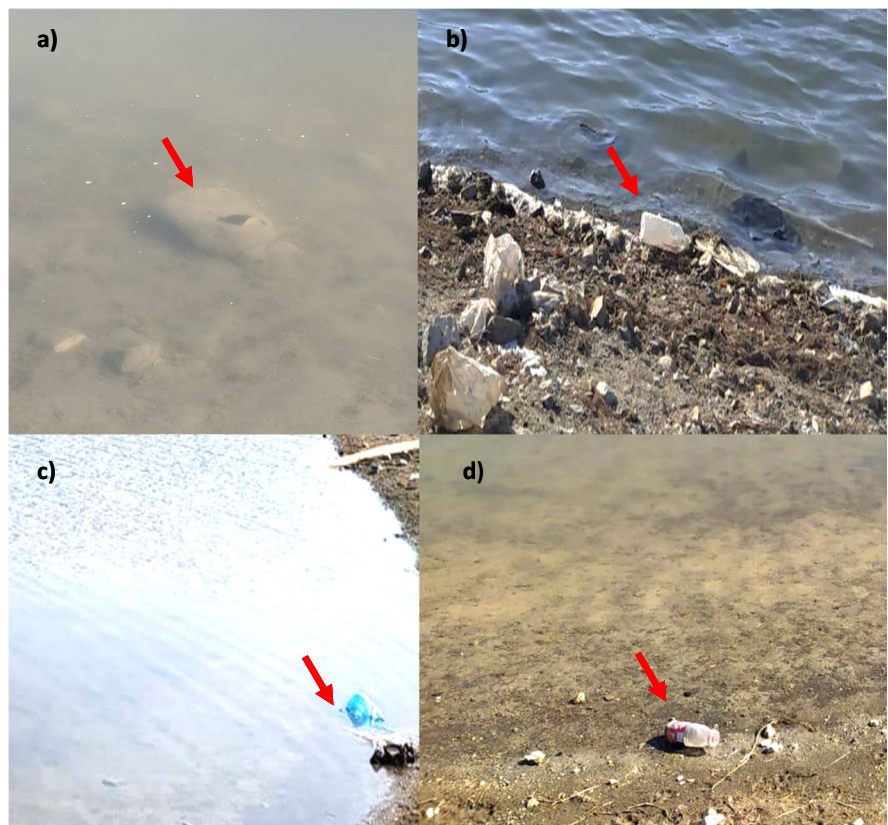


Fig. 2 Average MP concentrations (MP/L) for each station

and bags were frequently observed at these stations during the fieldwork. The average number of MPs determined in this study (2.4 MPs/L) is higher than the number detected in the Cevdet Dündar pond (0.2 MPs/L), which is also located in the same province (Erdogan, 2020). However, Cevdet Dündar pond is located within the protection area, thus human impact and related pollution levels are likely to be lower than unprotected water bodies. MP amount also differed among other freshwater studies, however higher MP concentrations were generally recorded in water bodies located in or near settlement areas (Grbić et al., 2020; Scopetani et al., 2019). Although Topçu pond is about 9 km away from the city center, it is frequently visited by the local people for fishing and recreational purposes. The pond is not exposed to human impact as much as the aquatic systems in the city centers, but plastic wastes thrown around the lake by visitors were observed during the study period (Fig. 3).

The most abundant MP type was fiber and observed in all stations (Fig. 4a). Similar to our results fiber was the most abundant MP type in

Fig. 3 Plastic bottles (a, b, and d) and plastic bags (c) observed on the pond shoreline



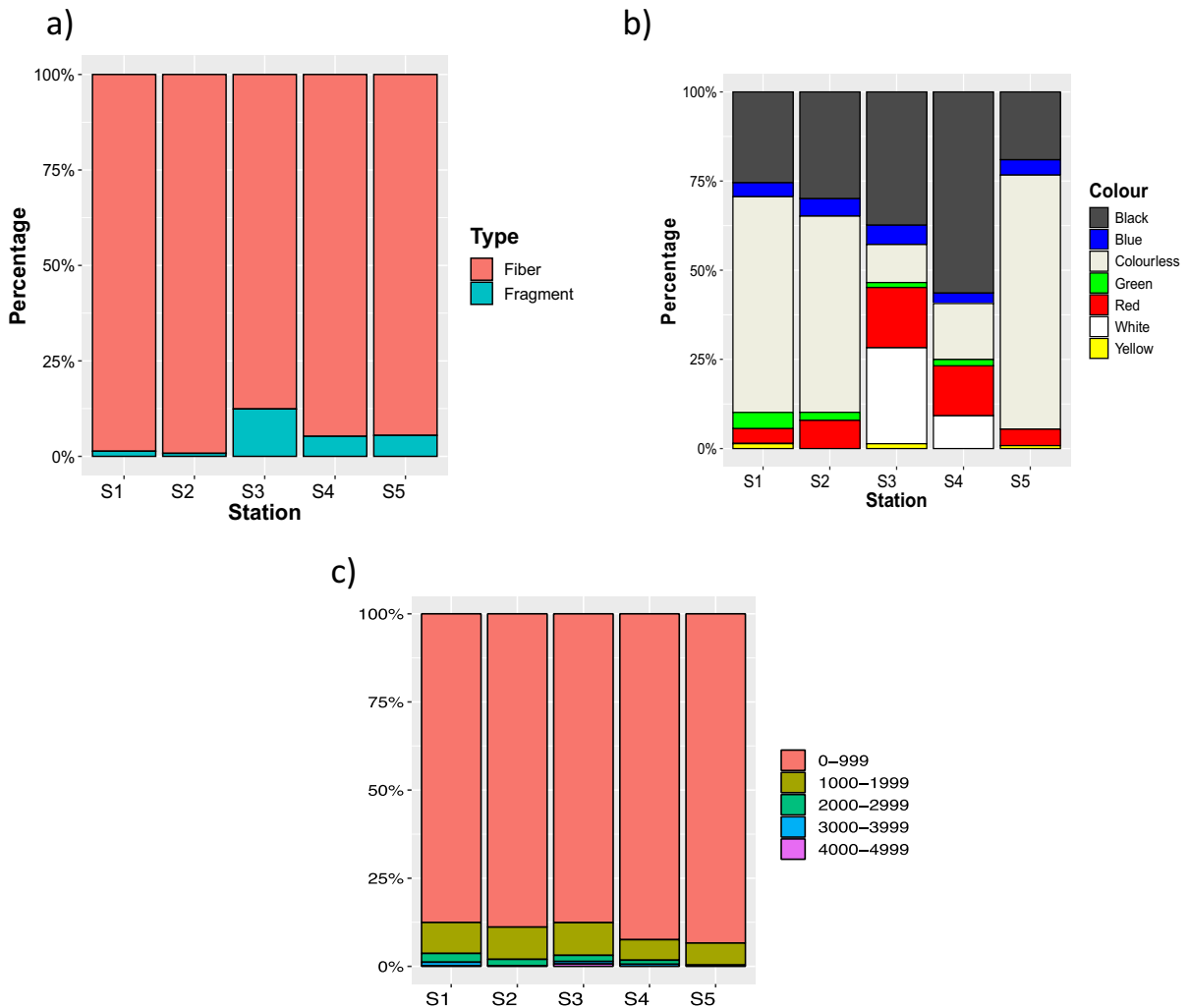


Fig. 4 a type, b color, and c size (μm)

many previous studies conducted in different freshwater ecosystems (Rebelein et al., 2021; Woods et al., 2018) what (Table 1). The breakdown of fishing gears over time might be the reason for the fiber dominance (Wang et al., 2018), the predominance of colorless fiber color also confirms this hypothesis. Even though the pond is located outside the city center airborne fiber transportation could be another fiber source (Prata et al., 2020). Buildings under construction close to the pond area and the highway passing nearby are probably also airborne fiber sources (Dris et al., 2016; Hüffer et al., 2019).

When the results are compared with two previous studies conducted in Yozgat province, it is seen that the amount of MPs detected in this study is higher than the others. One of the studies was carried out in Cevdet Dündar Pond, which has the status of a national park, and the pond is within the boundaries of the protected area, so less human impact may be the reason for less MP pollution (Erdogan, 2020). The other study was conducted in Süreyyabey Pond and again the amount of MP detected was less than in this study (Tavşanoğlu et al., 2020). However, the pore size of the net used in this study ($100\ \mu\text{m}$) is larger than the pore size of our

Table 1 Comparison of the abundance of MPs in freshwater bodies around the world

Location	Mesh size (µm)	Dominant polymer	Most abundant MP type	Total MP abundance (L)	References
Türkiye/Yozgat	61	PP-PE	Fiber	0.23	Erdogan (2020)
Türkiye/Erzurum	45	PP-PE			Çomaklı et al. (2020)
Türkiye/Yozgat	100	PP-PE-PET	Fiber	0.005	Tavşanoğlu et al. (2020)
Türkiye/Beyşehir	20	Cellophane	Fiber	0.003–0.007	Ulvi and Aydın (2023)
USA/Lake Victoria	300	PP-PE		0.001	Egessa et al. (2020)
India/Lake Red Hills	120	PP-PE	Fiber	5.9	Gopinath et al. (2020)
Switzerland/Lake Sassolo	63	PP-PE		2.6	Velasco et al. (2020)
This study	61	PP-PE	Fiber	2.4	

net (61 µm), this difference may have caused us to detect more MPs. When other studies conducted in different parts of the world are examined, the amount of MP detected in Red Hills (5.9 L) (Gopinath et al., 2020) and Saasola (2.6 L) (Velasco et al., 2020) lakes is higher than this study, whereas the amount of MPs detected in Victoria (0.001 L) (Egessa et al., 2020) lakes is less than the amount of MPs obtained in this study. However, although all the samples were taken from surface waters, the mesh sizes of the nets were different (Table 1).

In the production phase of plastic materials, many different additives are used to change the color, elasticity, and strength of the product. Black and colorless MP particles were the most abundant colors, and they were followed by red color (Fig. 4b). The reason for black color abundance could be the highway. As a consequence of the interactions between tires and road surfaces, tire abrasion causes the formation of small particles (Hüffer et al., 2019). Tires are typically made up of a complex mixture of polymers (40–60%); however, they also consist of natural materials (Lin & Teng, 2002). The ambient aerosol near all of the roads investigated is dominated by traffic-related abrasion particles, which account for approximately 90 vol% of the total amount (Sommer et al., 2018). In addition, since black color is frequently used in many plastic materials (single-use plastic bags, food packages, etc.), it may have caused the intense observation of black color. On the other hand, colorless MP abundance was also observed in previous studies conducted in freshwater ecosystems (Fu & Wang, 2019; Hu et al., 2020; X. Xu et al., 2021). MP released from fishing nets and ropes may be a significant source of these colorless MP fibers (Montarsolo

et al., 2018). Moreover, some parts of the colored fibers may lose their color, when exposed to water for an extended period of time (Hu et al., 2020).

The identified MP particles were classified into the following five size classes: <999 µm, 1000~1999 µm, 2000~2999 µm, 3000~3999 µm, and 4000~4999 µm (Fig. 4c). The most frequently observed size group was 0–999 µm. Small-size particles were the most abundant size group and this is in accordance with previous studies (Egessa et al., 2020; E. G. Xu et al., 2020). It is known that plastic materials produced in large sizes (primary plastic) break down over time and form smaller plastic particles (secondary plastic). There is a growing literature that demonstrates the potential for these small plastic particles to spread from their sources to a wide range of ecosystems, including aquatic systems (Bhat, 2024a, 2024b). As the size of MPs decreases, their consumption by small-sized aquatic organisms is likely to increase, and the transport of MPs through the food web will also increase.

Microplastic identification

According to the spectral library matches, the examined particles were identified as polypropene (40%), polyamide (30%), ethylene acrylic acid (20%), and polyvinylchloride (10%) (Fig. 5). Only two of the particles analyzed were found to be materials other than plastic. PP was the most identified polymer derivative, and it is one of the polymer types with the highest production on a global scale, for that reason, the result is not surprising and is in line with the results of other studies (Table 1) (Erdogan, 2020; K. Yin et al., 2021; L. Yin et al., 2019). One of the limitations of our study

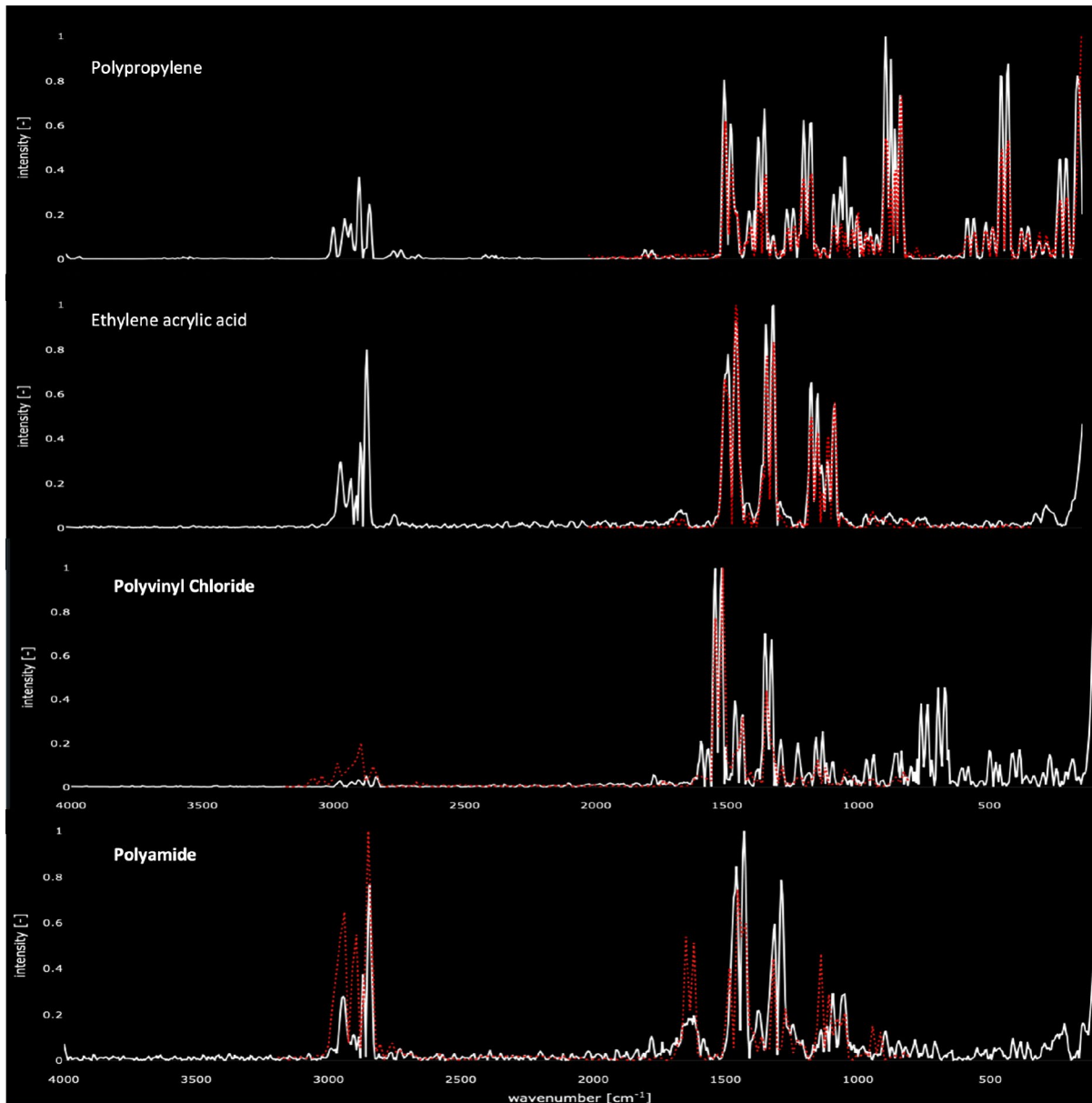


Fig. 5 Raman spectra of typical MPs

is that, although the highest proportion of particles detected at all stations was fiber, the particles analyzed by Raman spectroscopy were fragments. Raman spectra could not be obtained from fiber-type particles with sufficient accuracy to identify the polymer type. This problem has been observed also in previous studies (De Frond et al., 2023; Fang et al., 2024).

Fiber particles were stained with NR, which has been widely used in recent years for the verification of plastic materials (Cusworth et al., 2024; Meyers et al., 2022). Randomly selected fiber particles were stained with Nile red (N3013-Sigma) and examined under a fluorescence microscope. Fluorescence was detected in all stained particles (Fig. 6).

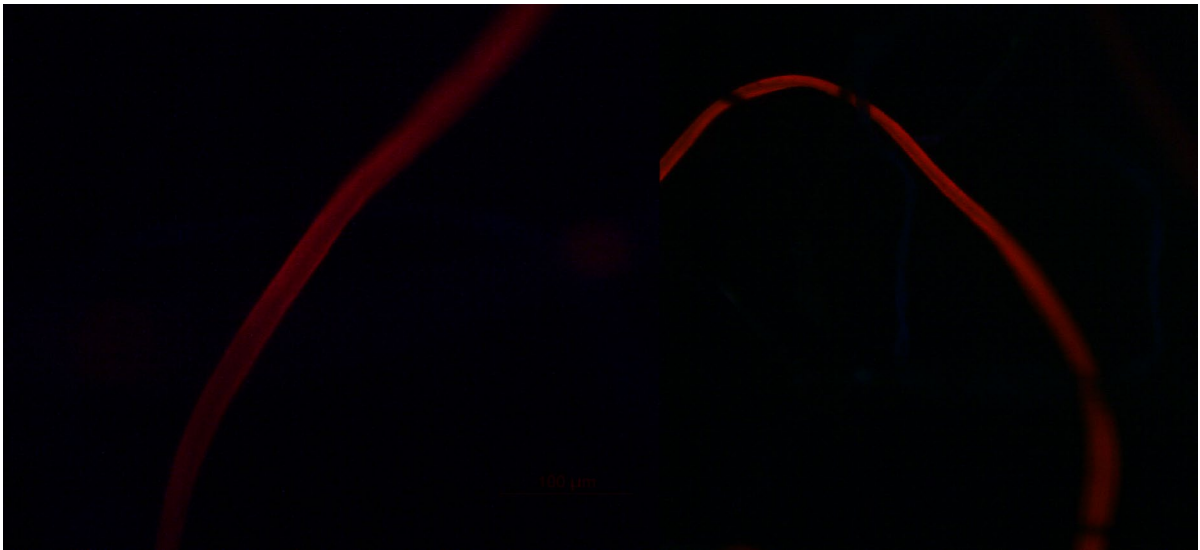


Fig. 6 Microplastic fibers particles dyed using Nile red

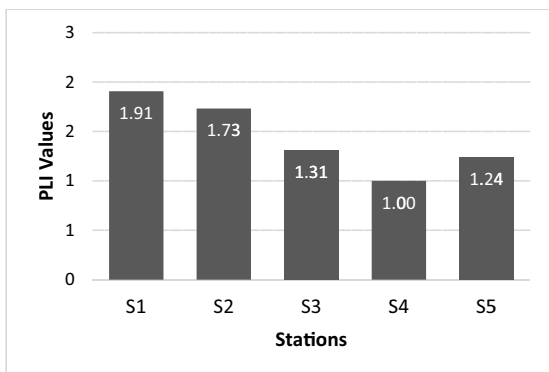


Fig. 7 Pollution load index values for each station

Pollution risk assessment

PLI values were determined as 1.91 at station S1, 1.73 at station S2, 1.31 at station S3, 1 at station S4, and 1.24 at station S5 (Fig. 7). The PLI value determined for the overall pond was 1.4. When PLI exceeds 1, the station is considered polluted by MPs. In this study, MP pollution was determined in all stations except station S4. Station S4 is at the limit value. According to the PLI values obtained, the order from the station with the highest pollution to the station with the lowest pollution is as follows; S1 > S2 > S3 > S5 > S4. The coastline where stations S1, S2, and S3 are located is used by local people for

fishing and recreation, and these stations are located close to the highway, so it is an expected result that MP pollution is higher at these stations.

Conclusion

In this study, MP abundance, size, color, type, and component materials were investigated in five stations in Topçu Pond. Average MP abundance was 2.4 MPs/L and in accordance with previous studies fiber was the dominant MP type in all stations. Small-sized particles and colorless/black-colored particles were abundant in all sampling sites. Based on Raman’s analysis, the majority of detected MPs were PP. Türkiye is a country with a population density of approximately 85 million and similar to many countries plastic production is increasing each year. However, research on MP pollution in different ecosystems has increased in recent years, but the number of researches is unfortunately not enough to understand the extent of MP pollution. The current study was the first comprehensive investigation of MP abundance in the Topçu Pond. However, this study has some limitations as well. Due to the budget limitation, the sampling could only be carried out once. A further study covering different seasons or months would allow for a more detailed understanding of the changes in the amount of pollution. Furthermore, in addition to

water samples, the analysis of MP pollution in sediment and pond biota will provide a detailed understanding of the amount of MP in the system and will help to reveal the effects of MP pollution on biota. A further limitation of MP studies is the lack of a standardized sampling method, which prevents the comparability of results across different studies. Nevertheless, the findings of this study are significant both as a baseline for future studies and as the first MP pollution study conducted in the region. Furthermore, this study is crucial in raising awareness among the general public and responsible state institutions.

Author contribution Serkan Caner: Formal analysis, Funding acquisition, Dilara Günay: Formal analysis, Hatice Arı: Formal analysis, editing, Şeyda Erdoğan: Supervision, Methodology, Conceptualization, Formal analysis, Writing-original draft, Investigation.

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Data availability Data will be made available on reasonable request.

Declarations

Ethics approval and consent to participate All authors have read, understood, and complied as applicable with the statement on “Ethical Responsibilities of Authors” as found in the instructions for authors.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

- Akgöz, C., & Güler, S. (2004). Algal Flora of Topçu Pond (Yozgat) AlgalFlora I: Epilittic and Epiphytic Algae. *Selçuk University Faculty of Science Journal of Science*, 1(23), 7–14.
- Amoatey, P., & Baawain, M. S. (2019). Effects of pollution on freshwater aquatic organisms. *Water Environment Research*, 91(10), 1272–1287. <https://doi.org/10.1002/wer.1221>
- Bartrons, M., Trochine, C., Blicharska, M., Oertli, B., Lago, M., & Brucet, S. (2024). Unlocking the potential of ponds and pondscapes as nature-based solutions for climate resilience and beyond: Hundred evidences. *Journal of Environmental Management*, 359, 120992. <https://doi.org/10.1016/J.JENVMAN.2024.120992>
- Bharath K, M., S, S., Natesan, U., Ayyamperumal, R., Kalam S, N., S, A., K, S., & C, A. (2021). Microplastics as an emerging threat to the freshwater ecosystems of Veeranam Lake in south India: A multidimensional approach. *Chemosphere*, 264, 128502. <https://doi.org/10.1016/J.CHEMOSPHERE.2020.128502>
- Bhat, M. A. (2024a). Airborne microplastic contamination across diverse university indoor environments: A comprehensive ambient analysis. *Air Quality, Atmosphere and Health*, 1–16. <https://doi.org/10.1007/S11869-024-01548-9/TABLES/1>
- Bhat, M. A. (2024b). A comprehensive characterization of indoor ambient microplastics in households during the COVID-19 pandemic. *Air Quality, Atmosphere and Health*. 1–17. <https://doi.org/10.1007/S11869-024-01559-6/TABLES/2>
- Bhat, M. A. (2024). Unveiling the overlooked threat: Macroplastic pollution in indoor markets in an urban city. *Case Studies in Chemical and Environmental Engineering*, 9, 100558. <https://doi.org/10.1016/J.CSCHEE.2023.100558>
- Bhat, M. A., Gaga, E. O., & Gedik, K. (2024). How can contamination be prevented during laboratory analysis of atmospheric samples for microplastics? *Environmental Monitoring and Assessment*, 196(2), 159. <https://doi.org/10.1007/S10661-024-12345-3>
- Bhat, M. A., & Janaszek, A. (2024). Evaluation of potentially toxic elements and microplastics in the water treatment facility. *Environmental Monitoring and Assessment*, 196(5), 475. <https://doi.org/10.1007/S10661-024-12651-W>
- Bhat, M. A., Mansoor, & Bhat, A. (2024). Microplastics in indoor deposition samples in university classrooms. *Discover environment* 2(1), 1–15. <https://doi.org/10.1007/S44274-024-00054-0>
- Biggs, J., von Fumetti, S., & Kelly-Quinn, M. (2016). The importance of small waterbodies for biodiversity and ecosystem services: Implications for policy makers. *Hydrobiologia*, 793(1), 3–39. <https://doi.org/10.1007/S10750-016-3007-0>
- Blettler, M. C. M. M., Ulla, M. A., Rabuffetti, A. P., Garello, N., Blettler, M. M. C., Alicia Ulla, M., Pia Rabuffetti, A., Garello, N., Blettler, M. C. M. M., Ulla, M. A., Rabuffetti, A. P., & Garello, N. (2017). Plastic pollution in freshwater ecosystems: Macro-, meso-, and microplastic debris in a floodplain lake. *Environmental Monitoring and Assessment*, 189(11), 581. <https://doi.org/10.1007/s10661-017-6305-8>
- Bos, R. P., Zhao, S., Sutton, T. T., & Frank, T. M. (2023). Microplastic ingestion by deep-pelagic crustaceans and fishes. *Limnology and Oceanography*, 68(7), 1595–1610. <https://doi.org/10.1002/LNO.12370>
- Chaudhari, S., & Samnani, P. (2023). Determination of microplastics in pond water. *Materials Today: Proceedings*, 77, 91–98. <https://doi.org/10.1016/J.MATPR.2022.10.141>
- Citterich, F., Lo Giudice, A., & Azzaro, M. (2023). A plastic world: A review of microplastic pollution in the freshwaters of the Earth's poles. *Science of the Total*

- Environment*,869, 161847. <https://doi.org/10.1016/J.SCITOTENV.2023.161847>
- Çomaklı, E., Bingöl, M. S., & Bilgili, A. (2020). Assessment of microplastic pollution in a crater lake at high altitude: A case study in an urban crater lake in Erzurum, Turkey. *Water, Air, and Soil Pollution*,231(6), 1–6. <https://doi.org/10.1007/S11270-020-04653-4/FIGURES/3>
- Cowger, W., Steinmetz, Z., Gray, A., Munno, K., Lynch, J., Hapich, H., Primpke, S., De Frond, H., Rochman, C., & Herodotou, O. (2021). Microplastic spectral classification needs an open source community: Open specy to the rescue! *Analytical Chemistry*. <https://doi.org/10.1021/acs.analchem.1c00123>
- Cuenca-Cambroner, M., Blicharska, M., Perrin, J. A., Davidson, T. A., Oertli, B., Lago, M., Beklioglu, M., Meerhoff, M., Arim, M., Teixeira, J., De Meester, L., Biggs, J., Robin, J., Martin, B., Greaves, H. M., Sayer, C. D., Lemmens, P., Boix, D., Mehner, T., ... Brucet, S. (2023). Challenges and opportunities in the use of ponds and pondscales as nature-based solutions. *Hydrobiologia*,850(15), 3257–3271. <https://doi.org/10.1007/S10750-023-05149-Y/METRICS>
- Cusworth, S. J., Davies, W. J., McAinsh, M. R., Gregory, A. S., Storkey, J., & Stevens, C. J. (2024). Agricultural fertilisers contribute substantially to microplastic concentrations in UK soils. *Communications Earth & Environment*,5(1), 1–5. <https://doi.org/10.1038/s43247-023-01172-y>
- De Frond, H., Cowger, W., Renick, V., Brander, S., Primpke, S., Sukumaran, S., Elkhatib, D., Barnett, S., Navas-Moreno, M., Rickabaugh, K., Vollnhals, F., O'Donnell, B., Lusher, A., Lee, E., Lao, W., Amarpuri, G., Sarau, G., & Christiansen, S. (2023). What determines accuracy of chemical identification when using microspectroscopy for the analysis of microplastics? *Chemosphere*,313, 137300. <https://doi.org/10.1016/J.CHEMOSPHERE.2022.137300>
- de Velasco, A. J. N., Rard, L., Blois, W., Lebrun, D., Lebrun, F., Pothe, F., & Stoll, S. (2020). Microplastic and fibre contamination in a remote mountain lake in Switzerland. *Water*,12(9), 2410. <https://doi.org/10.3390/W12092410>
- Dris, R., Gasperi, J., Saad, M., Mirande, C., & Tassin, B. (2016). Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin*,104(1–2), 290–293. <https://doi.org/10.1016/J.MARPOLBUL.2016.01.006>
- Earn, A., Bucci, K., & Rochman, C. M. (2021). A systematic review of the literature on plastic pollution in the Laurentian Great Lakes and its effects on freshwater biota. *Journal of Great Lakes Research*,47(1), 120–133. <https://doi.org/10.1016/J.JGLR.2020.11.001>
- Egessa, R., Nankabirwa, A., Ocaya, H., & Pabire, W. G. (2020). Microplastic pollution in surface water of Lake Victoria. *Science of the Total Environment*,741, 140201. <https://doi.org/10.1016/J.SCITOTENV.2020.140201>
- Erdogan, S. (2020). Microplastic pollution in freshwater ecosystems: A case study from Turkey. *Ege Journal of Fisheries and Aquatic Sciences*,37(3), 213–221. <https://doi.org/10.12714/egejfas.37.3.02>
- Fang, C., Awoyemi, O. S., Saianand, G., Xu, L., Niu, J., & Naidu, R. (2024). Characterising microplastics in indoor air: Insights from Raman imaging analysis of air filter samples. *Journal of Hazardous Materials*,464, 132969. <https://doi.org/10.1016/J.JHAZMAT.2023.132969>
- Fu, Z., & Wang, J. (2019). Current practices and future perspectives of microplastic pollution in freshwater ecosystems in China. *Science of the Total Environment*,691, 697–712. <https://doi.org/10.1016/J.SCITOTENV.2019.07.167>
- Gong, H., Li, R., Li, F., Xu, L., Gan, L., Li, J., Huang, H., Yan, M., & Wang, J. (2023). Microplastic pollution in water environment of typical nature reserves and scenery districts in southern China. *Science of the Total Environment*,903, 166628. <https://doi.org/10.1016/J.SCITOTENV.2023.166628>
- Gopinath, K., Seshachalam, S., Neelavannan, K., Anburaj, V., Rachel, M., Ravi, S., Bharath, M., & Achyuthan, H. (2020). Quantification of microplastic in Red Hills Lake of Chennai City, Tamil Nadu. *India. Environmental Science and Pollution Research*,27(26), 33297–33306. <https://doi.org/10.1007/S11356-020-09622-2/TABLES/2>
- Gosavi, S. M., & Phuge, S. K. (2023). First report on microplastics contamination in a meteorite impact crater lake from India. *Environmental Science and Pollution Research*,30(23), 64755–64770. <https://doi.org/10.1007/S11356-023-27074-2/FIGURES/7>
- Grbic, J., Helm, P., Athey, S., & Rochman, C. M. (2020). Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. *Water Research*,174, 115623. <https://doi.org/10.1016/J.WATRES.2020.115623>
- Heller, M. C., Mazor, M. H., & Keoleian, G. A. (2020). Plastics in the US: Toward a material flow characterization of production, markets and end of life. *Environmental Research Letters*,15(9), 094034. <https://doi.org/10.1088/1748-9326/ab9e1e>
- Horejs, C. (2020). Solutions to plastic pollution. *Nature Reviews Materials*,5(9), 641–641. <https://doi.org/10.1038/s41578-020-00237-0>
- Hossain, M. B., Banik, P., Nur, A. A., Choudhury, T. R., Liba, S. I., Albeshr, M. F., Yu, J., & Arai, T. (2023). Microplastics in fish culture ponds: Abundance, characterization, and contamination risk assessment. *Frontiers in Environmental Science*,11, 1251158. <https://doi.org/10.3389/FENV.2023.1251158/BIBTEX>
- Hu, D., Zhang, Y., & Shen, M. (2020). Investigation on microplastic pollution of Dongting Lake and its affiliated rivers. *Marine Pollution Bulletin*,160, 111555. <https://doi.org/10.1016/J.MARPOLBUL.2020.111555>
- Hüffer, T., Wagner, S., Reemtsma, T., & Hofmann, T. (2019). Sorption of organic substances to tire wear materials: Similarities and differences with other types of microplastic. *TrAC Trends in Analytical Chemistry*,113, 392–401. <https://doi.org/10.1016/J.TRAC.2018.11.029>
- Jiang, J. J., Hanun, J. N., Chen, K. Y., Hassan, F., Liu, K. T., Hung, Y. H., & Chang, T. W. (2023). Current levels and composition profiles of microplastics in irrigation water. *Environmental Pollution*,318, 120858. <https://doi.org/10.1016/J.ENVPOL.2022.120858>
- Joshi, C., Browning, S., & Seay, J. (2020). Combating plastic waste via trash to tank. *Nature Reviews Earth & Environment*,1(3), 142–142. <https://doi.org/10.1038/s43017-020-0032-3>

- Kurniawan, T. A., Haider, A., Ahmad, H. M., Mohyuddin, A., Umer Aslam, H. M., Nadeem, S., Javed, M., Othman, M. H. D., Goh, H. H., & Chew, K. W. (2023). Source, occurrence, distribution, fate, and implications of microplastic pollutants in freshwater on environment: A critical review and way forward. *Chemosphere*, 325, 138367. <https://doi.org/10.1016/J.CHEMOSPHERE.2023.138367>
- Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchey, M. R., Koskella, J., Velis, C. A., Godfrey, L., Boucher, J., Murphy, M. B., Thompson, R. C., Jankowska, E., Castillo Castillo, A., Pilditch, T. D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., ... Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, 369(6510), 1455–1461. <https://doi.org/10.1126/science.aba9475>
- Liang, Y., Tan, Q., Song, Q., & Li, J. (2021). An analysis of the plastic waste trade and management in Asia. *Waste Management*, 119, 242–253. <https://doi.org/10.1016/J.WASMAN.2020.09.049>
- Lin, Y.-R., & Teng, H. (2002). Mesoporous carbons from waste tire char and their application in wastewater discoloration. *Microporous and Mesoporous Materials*, 54(1–2), 167–174. [https://doi.org/10.1016/S1387-1811\(02\)00380-3](https://doi.org/10.1016/S1387-1811(02)00380-3)
- Mangal, M., Rao, C. V., & Banerjee, T. (2023). Bioplastic: An eco-friendly alternative to non-biodegradable plastic. *Polymer International*, 72(11), 984–996. <https://doi.org/10.1002/PI.6555>
- 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. NOAA Technical Memorandum NOS-OR&R-48
- Meyers, N., Catarino, A. I., Declercq, A. M., Brenan, A., Devriese, L., Vandegheuchte, M., De Witte, B., Janssen, C., & Everaert, G. (2022). Microplastic detection and identification by Nile red staining: Towards a semi-automated, cost- and time-effective technique. *Science of the Total Environment*, 823, 153441. <https://doi.org/10.1016/J.SCITOTENV.2022.153441>
- Montarsolo, A., Mossotti, R., Patrucco, A., Caringella, R., Zoccola, M., Pozzo, P. D., & Tonin, C. (2018). Study on the microplastics release from fishing nets. *The European Physical Journal plus*, 133(11), 494. <https://doi.org/10.1140/epjp/i2018-12415-1>
- Mutlu, T., Minaz, M., Baytaşoğlu, H., & Gedik, K. (2024). Monitoring of microplastic pollution in sediments along the Çoruh River Basin, NE Türkiye. *Journal of Contaminant Hydrology*, 263, 104334. <https://doi.org/10.1016/J.JCONHYD.2024.104334>
- Nor, N. H., & Obbard, J. P. (2014). Microplastics in Singapore's coastal mangrove ecosystems. *Marine pollution bulletin*, 79(1-2), 278–283. <https://doi.org/10.1016/j.marpolbul.2013.11.025>
- Patrício Silva, A. L., Prata, J. C., Walker, T. R., Campos, D., Duarte, A. C., Soares, A. M. V. M., Barcelò, D., & Rocha-Santos, T. (2020). Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. *Science of the Total Environment*, 742, 140565. <https://doi.org/10.1016/J.SCITOTENV.2020.140565>
- Prata, J. C., Castro, J. L., da Costa, J. P., Duarte, A. C., Rocha-Santos, T., & Cerqueira, M. (2020). The importance of contamination control in airborne fibers and microplastic sampling: Experiences from indoor and outdoor air sampling in Aveiro, Portugal. *Marine Pollution Bulletin*, 159, 111522. <https://doi.org/10.1016/J.MARPOLBUL.2020.111522>
- Prunier, J. G., Dubut, V., Loot, G., Tudesque, L., & Blanchet, S. (2018). The relative contribution of river network structure and anthropogenic stressors to spatial patterns of genetic diversity in two freshwater fishes: A multiple-stressors approach. *Freshwater Biology*, 63(1), 6–21. <https://doi.org/10.1111/fwb.13034>
- Rebelein, A., Int-Veen, I., Kammann, U., & Scharsack, J. P. (2021). Microplastic fibers — Underestimated threat to aquatic organisms? *Science of the Total Environment*, 777, 146045. <https://doi.org/10.1016/J.SCITOTENV.2021.146045>
- Savitzky, A., & Golay, M. J. E. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, 36(8), 1627–1639. https://doi.org/10.1021/AC60214A047/ASSET/AC60214A047.FP.PNG_V03
- Scopetani, C., Chelazzi, D., Cincinelli, A., & Esterhuizen-Londt, M. (2019). Assessment of microplastic pollution: Occurrence and characterisation in Vesijärvi lake and Pikku Vesijärvi pond, Finland. *Environmental Monitoring and Assessment*, 191(11), 652. <https://doi.org/10.1007/s10661-019-7843-z>
- Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C., & Gieré, R. (2018). Tire abrasion as a major source of microplastics in the environment. *Aerosol and Air Quality Research*, 18(8), 2014–2028. <https://doi.org/10.4209/aaqr.2018.03.0099>
- Stone, C., Windsor, F. M., Munday, M., & Durance, I. (2020). Natural or synthetic – How global trends in textile usage threaten freshwater environments. *Science of the Total Environment*, 718, 134689. <https://doi.org/10.1016/J.SCITOTENV.2019.134689>
- Tavşanoğlu, Ü. N., Başaran Kankılıç, G., Akca, G., Çırak, T., & Erdoğan, Ş. (2020). Microplastics in a dam lake in Turkey: Type, mesh size effect, and bacterial biofilm communities. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-020-10424-9>
- Thacharodi, A., Meenatchi, R., Hassan, S., Hussain, N., Bhat, M. A., Arockiaraj, J., Ngo, H. H., Le, Q. H., & Pugazhendhi, A. (2024). Microplastics in the environment: A critical overview on its fate, toxicity, implications, management, and bioremediation strategies. *Journal of Environmental Management*, 349, 119433. <https://doi.org/10.1016/J.JENVMAN.2023.119433>
- Tomlinson, D.L., Wilson, J.G., Harris, C.R. and Jeffrey, D.W. (1980) Problems in the Assessment of Heavy-Metal Levels in Estuaries and the Formation of a Pollution Index. *Helgoländer Meeresuntersuchungen*, 33, 566-575. <https://doi.org/10.1007/BF02414780>
- Ulvi, M., & Aydin, S. (2023). Microplastic and associated polyaromatic hydrocarbons in surface waters feeding Beyşehir Lake in Türkiye. *Global Nest Journal*, 25(7), 91–98. <https://doi.org/10.30955/GNJ.004960>

- Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbins, J., & Janssen, C. R. (2015). Microplastics in sediments: A review of techniques, occurrence and effects. *Marine Environmental Research*, *111*, 5–17. <https://doi.org/10.1016/J.MARENVRES.2015.06.007>
- 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>
- Wen, Z., Xie, Y., Chen, M., & Dinga, C. D. (2021). China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nature Communications*, *12*(1), 425. <https://doi.org/10.1038/s41467-020-20741-9>
- Woods, M. N., Stack, M. E., Fields, D. M., Shaw, S. D., & Matrai, P. A. (2018). Microplastic fiber uptake, ingestion, and egestion rates in the blue mussel (*Mytilus edulis*). *Marine Pollution Bulletin*, *137*, 638–645. <https://doi.org/10.1016/J.MARPOLBUL.2018.10.061>
- Wright, J., Hovey, R. K., Paterson, H., Stead, J., & Cundy, A. (2023). Microplastic accumulation in *Halophila ovalis* beds in the Swan-Canning Estuary, Western Australia. *Marine Pollution Bulletin*, *187*, 114480. <https://doi.org/10.1016/J.MARPOLBUL.2022.114480>
- Xu, E. G., Cheong, R. S., Liu, L., Hernandez, L. M., Azimzada, A., Bayen, S., & Tufenkji, N. (2020). Primary and secondary plastic particles exhibit limited acute toxicity but chronic effects on *Daphnia magna*. *Environmental Science & Technology*, *54*(11), 6859–6868. <https://doi.org/10.1021/acs.est.0c00245>
- Xu, X., Zhang, L., Xue, Y., Gao, Y., Wang, L., Peng, M., Jiang, S., & Zhang, Q. (2021). Microplastic pollution characteristic in surface water and freshwater fish of Gehu Lake, China. *Environmental Science and Pollution Research*, 1–11. <https://doi.org/10.1007/s11356-021-15338-8>
- Yabanlı, M., Yozukmaz, A., Şener, İ., & Ölmez, Ö. T. (2019). Microplastic pollution at the intersection of the Aegean and Mediterranean Seas: A study of the Datça Peninsula (Turkey). *Marine Pollution Bulletin*, *145*, 47–55. <https://doi.org/10.1016/J.MARPOLBUL.2019.05.003>
- Yin, K., Wang, D., Zhao, H., Wang, Y., Guo, M., Liu, Y., Li, B., & Xing, M. (2021). Microplastics pollution and risk assessment in water bodies of two nature reserves in Jilin Province: Correlation analysis with the degree of human activity. *Science of the Total Environment*, *799*, 149390. <https://doi.org/10.1016/J.SCITOTENV.2021.149390>
- Yin, L., Jiang, C., Wen, X., Du, C., Zhong, W., Feng, Z., Long, Y., & Ma, Y. (2019). Microplastic pollution in surface water of urban lakes in Changsha, China. *International Journal of Environmental Research and Public Health*, *16*(9), 1650. <https://doi.org/10.3390/ijerph16091650>
- Zhao, C., Liu, M., Du, H., & Gong, Y. (2021). The evolutionary trend and impact of global plastic waste trade network. *Sustainability*, *13*(7), 3662. <https://doi.org/10.3390/su13073662>
- Zhao, J., Lui, H., Mclean, D. I., & Zeng, H. (2007). Automated autofluorescence background subtraction algorithm for biomedical Raman spectroscopy. *Applied Spectroscopy*, *61*(11), 1225–1232. <https://doi.org/10.1366/000370207782597003>

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