Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-20403-x

RESEARCH ARTICLE

Microplastics distribution and possible ingestion by fish in lacustrine waters (Lake Bracciano, Italy)

Alessandra Cera[1] · **Maria Sighicelli**[2] · **Armida Sodo**[1] · **Francesca Lecce**[2] · **Patrizia Menegoni**[2] · **Massimiliano Scalici**[1]

Received: 20 January 2022 / Accepted: 19 April 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract

Understanding the spatial distribution patterns of microplastics (plastics < 5 mm) contributes to the assessment of sources and sinks of pollution thus providing information for the management of biota safety and overall ecosystem functionality. We chose a semi-closed study area, Lake Bracciano (Italy), to assess the environmental variability of contamination, focusing on the water compartment and the exposure of biota, specifically fish, by analysing the ingestion of microplastics. The focus of this study is to evaluate the concentration of microplastics in water (surface and column) across the lake and the ingestion of microplastics by two fish species of economic interest: *Atherina boyeri* and *Coregonus lavaretus*, inhabiting demersal and pelagic habitats respectively. Results show a surface contamination of 392,000 ± 417,000 items km^{-2} and a column one of 0.76 ± 1.00 items m^{-3}. Fragments were the most abundant in surface while fibres in the column. Microplastics were found in *C. lavaretus* specimens, corresponding to contamination frequency of 5% and concentration of 0.15 items/fish. The main polymer found in water was polyethylene (81%); of minor percentages, there were various other polymers, including polystyrene and acrylic, which were also found in fish. As scientific literature provides few research where water and fish are simultaneously sampled, this investigation wants to contribute filling this knowledge gap by investigating for the first time a volcanic lake.

Keywords Microplastics · Wild fish · Planktofagous fish · Gastrointestinal tract · Lentic freshwater · Volcanic lake · Monomictic lake · Lake Bracciano

Introduction

Plastics are anthropogenic persistent organic pollutants which contaminate ecosystems worldwide due to combination of high production rates, durability, inappropriate use of plastic products, and insufficient or non-existent waste management (Barnes et al. 2009; Lambert and Wagner 2018). Scientific literature started investigating the mismanaged plastics contaminating the oceans since the ‘70 s, and the scientific productivity has increased since then, until plastic pollution has become a hot topic of research (Ryan 2015). In particular, the effects of plastic pollution on organisms were investigated, finding that plastics can impact negatively the organisms, inducing suffocation, entanglement, gastrointestinal damage and ultimately death (Gregory 2009).

The plastic particles sized between 1 µm and 5 mm are called microplastics (MPs) (Frias and Nesh 2019; Gilgault et al. 2018; Thompson et al. 2004). If MPs are produced by industrial activities, they are called primary MPs (GESAMP 2016), while if the MPs are generated by the environmental breakdown of larger plastics due to thermal, photo-oxidative or mechanical stimuli (Singh and Sharma 2008), they are called secondary MPs (GESAMP 2016).

MPs can contaminate the air, soil and water. In particular, MPs were detected in the atmosphere even in remote areas,

---

Communicated by Ester Heath.

✉ Alessandra Cera
alessandra.cera@uniroma3.it

Maria Sighicelli
maria.sighicelli@enea.it

Armida Sodo
armida.sodo@uniroma3.it

Massimiliano Scalici
massimiliano.scalici@uniroma3.it

[1] Department of Sciences, University of Roma Tre, Viale G. Marconi 446, 00146 Rome, Italy

[2] Department for Sustainability (SSPT), ENEA, C.R, Casaccia-Via Anguillarese 301, 00123 Rome, Italy

Published online: 10 May 2022

suggesting that their wind-induced transport can reach long distances; however, the study of MPs in the air has recently started and requires further investigations (Zhang et al. 2020). As regards soils, MPs can contaminate the surface of soil or migrate vertically through it, and they can impact soil communities (Guo et al. 2020). MPs in aquatic environments occur both in marine and inland ecosystems (Katare et al. 2022), although the latter is less investigated (Blettler et al. 2018).

Focusing on freshwater ecosystems, research has been increasing in recent years, but it has been investigating lotic ecosystems more than lentic ecosystems (Cera et al. 2020). The available information has established that MPs are abundant and widespread but unevenly distributed geographically (Cera et al. 2020). However, reports are lacking from many geographical areas, especially South America, Africa and Oceania (Cera et al. 2020). The sources of freshwater pollution by MPs are numerous and can include the cloth washing, fishing and recreational activities, industrial by-products and the contamination by air and soil (Kurniawan et al. 2021). Once dispersed into the environments, MPs do not distribute equally between the environmental matrices (i.e. water and sediments). The sediments are generally more contaminated than the waters; thus, sediment is defined as MP sink (Cera et al. 2020). As regards water, lake water is usually more contaminated than river water (Cera et al. 2020). Similar factors influencing MPs pollution affect rivers and lakes, both natural and anthropogenic. In detail, among natural factors, the occurrence of surface runoff, storms and floods (Cheung et al. 2019; Hurley et al. 2018; Piñon-Colin et al. 2020); the size of the water body and the action of wind can influence the transport of MPs (Free et al. 2014). As regards anthropic factors, the proximity to higher density of human population and urban areas increase the abundance of MPs in lakes (Wang et al. 2017) and rivers (Kataoka et al. 2019). In addition, the lack of protection measurements for plastic waste increases the occurrence and abundance of MPs (Yin et al. 2019; Zhang et al. 2016).

Laboratory research has proven various negative effects of MPs on different freshwater species, for instance inducing the activation of stress response genes (Xu et al. 2020). MPs can also be transferred across the food web, affecting higher trophic levels (Castro-Castellon et al. 2021). The overall risk of negative impacts on freshwater ecosystems induced by MPs is considered a relevant issue, as field studies have proven that a high exposure of organisms to MPs is frequently occurring in both lentic and lotic ecosystems (Cera et al. 2022). Several observations on MPs and free-living biota were assessed by field studies, for instance microorganisms can colonise buoyant MPs and form communities significantly different from the surrounding water (Di Pippo et al. 2020); the larvae of Trichopterans can include MPs in their protective cases (Gallitelli et al. 2021); and the ingestion of MPs is frequently observed in various taxa of both vertebrates and invertebrates (e.g. Andrade et al. 2019; Holland et al. 2016; Schessl et al. 2019). In particular, the ingestion of MPs by freshwater biota is highly reported data, especially in fish (Cera and Scalici 2021). Scientific literature reports the contamination of fish gastrointestinal tracts (GITs) by MPs since 2015 (Faure et al. 2015). Throughout the years, the frequency of GIT contamination has been assessed in numerous fish species, and it has shown to differ globally, ranging from no contamination to 100% contamination (e.g. Faure et al. 2012; Galafassi et al. 2021; Xiong et al. 2018). Several factors are proposed to explain the variability of occurrence and abundance of MPs in GIT, such as species, the trophic level, diet, GIT morphology and season (Gouin 2020). To date, scientific literature limitedly provides a clear standardised pattern explaining the differences in GIT contamination of fish (Cera and Scalici 2021). However, it is undoubted that the contamination of environmental matrices of the study area plays a fundamental role in GIT contamination. Current scientific literature limitedly investigates the link between environmental contamination and MP ingestion by fish in lentic fresh water.

In the optic to contribute to the scientific debate on the distribution of MPs in lentic freshwater, this study aims to (i) analyse the distribution of MPs in water surface and column (from − 50 m to surface) and (ii) detect the GIT contamination of commercial fish species inhabiting demersal and pelagic habitats as they are expected to be the most exposed to water contamination.

Materials and methods

Study area

The study was conducted in Lake Bracciano (Central Italy), a sub-circular volcanic-tectonic depression belonging to Sabatini Volcanic District (De Rita et al. 1996; Nicolosi et al. 2019). The lake has an altitude of 164 m, area of 57 km^2, volume of 5 km^2, max depth of 160 m, mean depth of 88 m, and a retention time of 137 years (Ministero dell'ambiente e della tutela del territorio e del mare 2007; Stella 1984; Taviani and Henriksen 2015). It is an oligo-mesotrophic, meromictic, warm monomictic lake (Barbanti et al. 1996; Ferrara et al. 2002). It has minor tributaries (Baccetti et al. 2017; Margaritora et al. 2003) and one emissary (i.e. River Arrone), which is dry in the upper part since recent years (Mazza et al. 2015). Lake Bracciano was chosen as study area because it has the unique characteristic of being a semi-closed space. In fact, the absence of major tributaries or emissaries limits the ingression of biota into the lake. Therefore, the observations conducted on fish from Lake Bracciano are considered to represent local processes of contamination with a greater confidence in data accuracy. Lake Bracciano is protected by the Regional Park “complesso lacuale di Bracciano Martignano” since 1987 (Regional Law number 36/99). Moreover, it belongs to the Mediterranean biogeographic region Special Protected Area named “Comprensorio Bracciano-Martignano” (code IT6030085). In recent years, it has become a Site of Community Importance named “Lago di Bracciano” (code IT6030010) and a Special Area of Conservation (Ministerial Decree 06/12/2016) of Natura 2000 ecological network (Decision n. 2019/22 of the European Commission—document reference number C(2018) 8534). Furthermore, since 2020, Lake Bracciano has been a pilot area of the Blue Lakes project (LIFE18 GIE/IT/000813) for the development of the monitoring protocol of MPs in the lakes (Blue Lakes project LIFE 2018–2023).

Water sampling

Water sampling in Lake Bracciano (BR) was carried out in July 2019 during the 14th edition of Goletta dei Laghi (GdL) that annually monitors water quality of the main Italian lakes. Ten transects (from BR1 to BR10) were selected from different sectors of the lake (Fig. 1). Transects from BR1 to BR6 belong to the northern sector while transects BR7-BR10 belong to the southern sector. Surface water samples were collected using a manta trawl with an ultrafine mesh (330 µm mesh size and 40 × 20 cm opening), which was dropped and dragged by the boat and immersed 20 cm below the surface while maintaining along the windward boat side. The manta filtered a mean of 80 m^3 of surface water at an average trawling speed of 2 km for 15 min. Direction trawling was chosen considering the dominant wind directions and current water location in the study area according to accepted sampling methodology (Hidalgo-Ruz et al. 2012).

Column water samples were collected by plankton net (80 µm mesh size and 28 cm opening) from a depth of 50 m in the same transects of surface samplings. The vertical net filtered a mean of 3 m^3 of column water in 3 min at a recovery speed of 0.28 m/s.

Fish sampling and data collection

Fish sampling was conducted during summer stagnation phase in 2019, concurrently with water samplings. We selected two fish species in order to include different trophic and elective habitat characteristics, which are considered potential factors influencing plastic ingestion: *Atheryna boyeri* Risso 1810 and *Coregonus lavaretus* (Linnaeus, 1758). As diet regards, *A. boyeri* feeds on zooplankton and benthic invertebrates while *C. lavaretus* feeds only on zooplankton. Concerning the habitats, *A. boyeri* is a demersal species while *C. lavaretus* is pelagic. These species had also the advantage of being among the ones of commercial interest which are regularly fished by local professional fishermen. The collaboration with local citizens in the optic of establishing a connection with the scientific world is a common practice by the citizen science (Ferreira-Rodríguez et al. 2020; Jesus et al. 2021). Hence, we involved the professional fishermen asking them for collaboration in this project by providing us fish. By the means of informal talking, the issue of MPs was described to the fishermen, which showed a collaborative attitude. The use of citizen science provided a positive feedback for this research.

Biological parameters of fish were collected in laboratory. First, fish were weighed (W), and the standard length (SL) was measured. The allometric coefficient (*b*) and the condition index (*K*) were calculated to assess the health of the individuals by the following formula: $K = 100\ W/SL^b$. Thereafter, fish were dissected to determine the sex by the

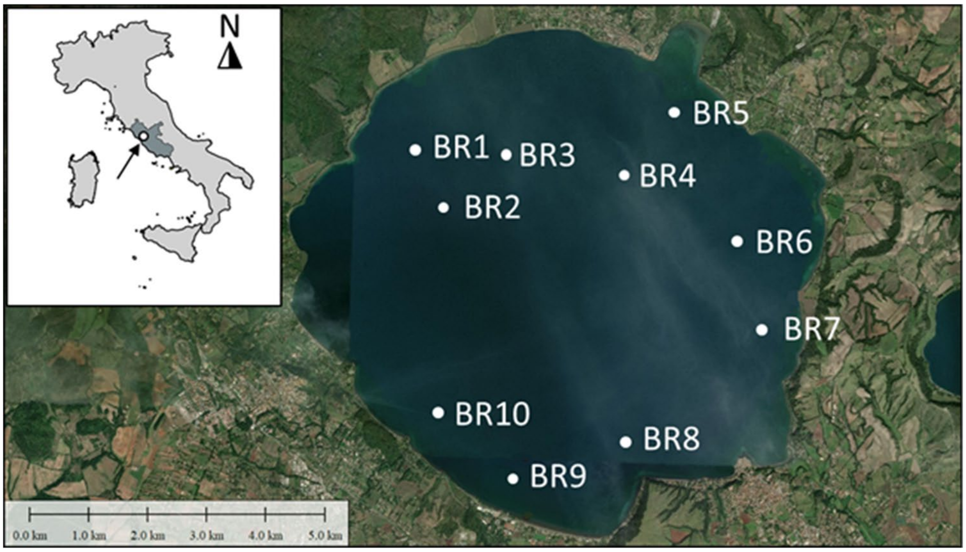

Fig. 1 Location of sampling transects in Lake Bracciano

observation of primary and secondary dimorphic characters. The whole GIT was extracted for the analysis on diet and on plastics, since some species could better entrap MPs in the stomach while other species in the intestine (Jabeen et al. 2017). The GIT was dissected on a Petri dish and the contents observed under a stereomicroscope to conduct a taxonomic identification of preys and to detect MPs (Roch et al. 2019).

MP identification in water

The collected water samples were preliminary washed, and the plastics were sieved and manually separated from the organic matter using a stereomicroscope. After drying at 50 °C, the particles were counted and sorted in categories based on shape (i.e. fragment, fibre, bead) (Sighicelli et al. 2018). MP abundance was determined in all 20 trawl samples and estimated in items km^{-2} and items m^{-3}. Fourier-transform infrared (FT-IR) spectra were collected in attenuated total reflectance (ATR) mode using ThermoFisher Scientific Nicolet iS5 spectrometer; spectrum range was 4000–400 cm^{-1} and the resolution of 4 cm^{-1}. Chemical composition of polymer particles was identified by comparison with reference spectra database of Thermo Scientific™ OMNIC™ Series Software (match threshold $r \geq 0.80$).

MP identification in fish

The MP items in the GIT contents were inspected for consistency and shape based on visual analysis by stereomicroscope (Ferreira et al. 2019). They were photographed with a reference scale to measure them by Image Tool 2.0 software. The presence, abundance, shape (i.e. fragment, fibre, bead) and colour (i.e. red, orange, yellow, green, blue, violet, black, white, clear) of plastics were noted (Lusher et al. 2020).

An InVia Renishaw Micro-Raman spectrometer equipped with a Leica DM2700 M confocal microscope was used to analyse all suspected plastic items from field and control samples. Two objectives, an Olympus 20 × LWD and a Leica 50 × LWD, have been used to focus the beam down to few microns (≈ 5 µm). Two solid-state diode laser sources, one at 532 nm (nominal output 100 mW) and the other at 785 nm (nominal output 200 mW), have been used. The high-contrast rejection for elastically scattered light is provided by holographic edge filters. An elastically scattered light is dispersed by an 1800 line/mm diffraction grating suitable to achieve a spectral resolution of 1 cm^{-1} when using the 532 nm excitation wavelength; a 1200 line/mm grating has been used with primary wavelength of 785 nm instead. A Peltier cooled 1024 × 256 pixel CCD detector collects the dispersed light. Raman spectra have been collected in the 100–3200 cm^{-1} range. To achieve suitable statistics, an integration time of about 10 s and 1 accumulation has been found to be adequate for most of the investigated samples. Wire software has been used to set the experimental conditions. The identification of spectra used a free available software, i.e. SpectraGryph (Menges 2020), and reference spectra from literature. Specifically, Raman reference spectra were obtained by databases “SLOPP” and “SLOPP-E” (Munno et al. 2020) and scientific articles (e.g. Bokobza et al. 2015).

The values of similarities below 60% were not accepted (European Commission 2013). If the value of similarity was above 60%, the sample and reference spectra are confirmed visually by a researcher.

Quality control procedures

The working station was cleaned with EtOH prior usage and a cotton coat, and latex gloves were always worn. The exposure of samples to air was kept to minimum by covering the Petri dishes with lids. A clean Petri dish was placed on the working station next to the stereomicroscope used for the visual identification of MPs to detect airborne contamination in water samples. The equipment used for the dissection of GITs and Petri dishes were previously rinsed with distilled water then visually inspected under stereomicroscope to check the presence of contamination. Three procedural blanks were conducted for fish (Koelmans et al. 2019). In addition, if the spectra of the MPs in samples were detected also in the controls, that data was considered not acceptable because of possible contamination.

Results

Water

The controls showed no contamination of water samples by MPs. The mean concentration of MPs is 392,000 ± 417,000 items km^{-2} (corresponding to 1.29 ± 1.59 items m^{-3}) for surface samplings. The minimum concentration is 31,000 items km^{-2} (corresponding to 0.16 items m^{-3}) and was detected in station 10 in the southern area, while the maximum concentration is 1,400,000 items km^{-2} (corresponding to 4.9 items m^{-3}) and was detected in station 5 in the northern area (Fig. 3a). Regarding column samplings, the mean concentration of MPs is 0.76 ± 1.00 items m^{-3}. The minimum concentration is 0 items m^{-3} mainly in the southern stations, and the maximum concentration is 2.6 items m^{-3} in station 2 (Fig. 2b).

Regarding the shape of MPs observed, surface samplings show a prevalence of fragments (80%) while column sampling show a prevalence of fibres (57%) (Fig. 3a, b). The difference between the shapes of surface and column samplings is significantly different (Chi squared test, df = 1, $p < 0.01$) (bead frequency is not included in the chi-squared test analysis as its value is zero).

Polyethylene (PE) is the main polymer of MP detected (80.8%); specifically, chlorinated polyethylene (CPE) has the majority of occurrence (72.2%) (Fig. 4). Other polymers detected include resin acrylic (4%), polypropylene (PP) (3.2%), polystyrene (PS) (3%), polyester (PL) (2.8%), epoxy resin (2.6%), urea formaldehyde resin (UF) (1.4%), polyethylene terephthalate (PET) (1%) and polyamide resin (PA) (0.2%) (Fig. 4).

Fish

Fifty-six fish were collected from Lake Bracciano, divided in 36 *A. boyeri* and 20 *C. lavaretus* (Supplementary Information 1). The frequency of males is not significantly different from the one of females (Supplementary Information 1). Most GITs of *A. boyeri* were empty (19% were full)

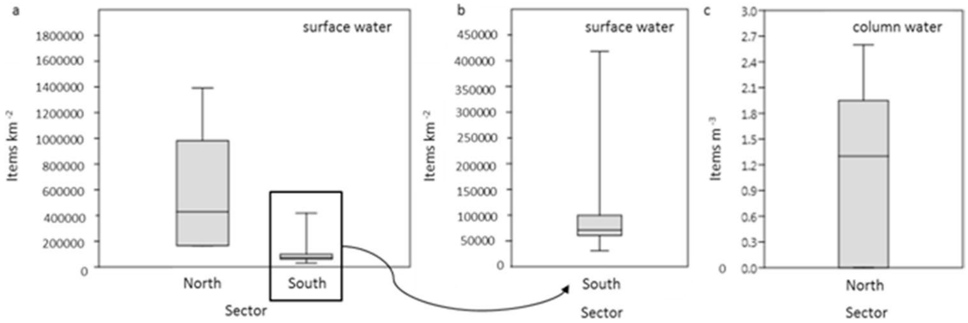

Fig. 2 **a** MP concentration in surface water; **b** focus on the surface water contamination of the southern sector; **c** MP concentration in column water (no microplastics were detected in the southern sector)

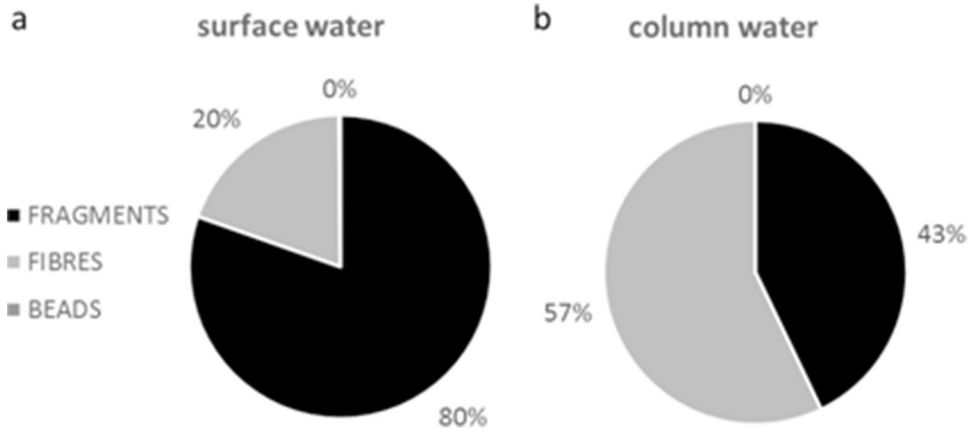

Fig. 3 Frequency (%) of the MPs shape detected in **a** surface water and **b** column water

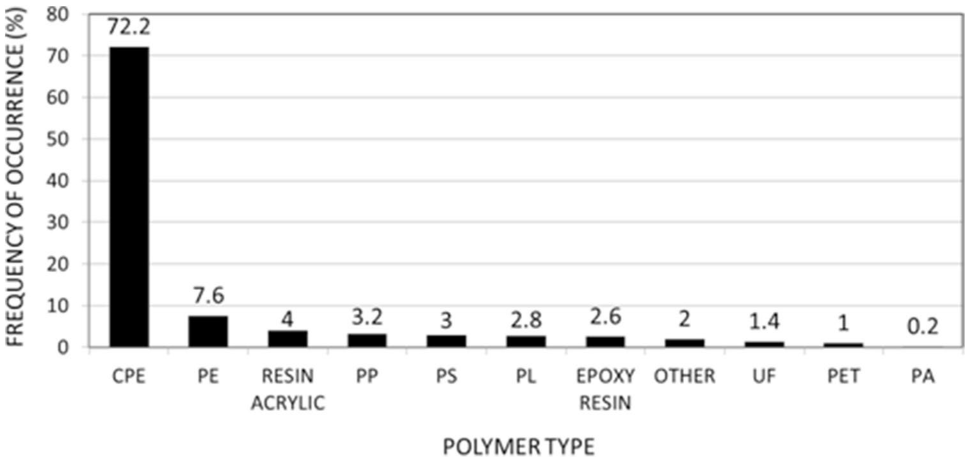

Fig. 4 Frequency (%) of polymers detected in water samples. CPE chlorinated polyethylene; PE polyethylene; PP polypropylene; PS polystyrene; PL polyester; UF urea formaldehyde resin; PET polyethylene terephthalate; PA polyamide resin

while most GITs of *C. lavaretus* were full (95%). Regarding diet, the observation show: Cladocera, adult Hymenoptera, Diptera and Trichoptera larvae in *A. boyeri*; Caldocera and Copepoda in *C. lavaretus.* Only one GIT of *C. lavaretus* was contaminated by MPs, resulting in 5% of occurrence if only *C. lavaretus* is considered and 1.8% if the whole sample is considered. The total number of MPs detected was 3, so the mean contamination results as 0.15 ± 0.67 MPs per *C. lavaretus* and 0.05 ± 0.40 MPs per the whole fish sample. The MPs were three red fibres 1.1 mm, 2.7 mm and 3.6 mm long. Micro Raman analysis identified two PS combined with an unidentified azodye colorant and one red acrylic spectrum (Fig. 5).

The biological parameters of the contaminated specimen are within the variance of the conspecific fish samples in regard to length and mass (Supplementary Information 1). Based on the calculated K, the contaminated *C. lavaretus* has a higher K (K = 459) than the mean of other conspecific (K = 440) (Supplementary Information 2). The GIT of the *C. lavaretus* contaminated by MPs include plankton; thus, it is representative of the results of diet observed in the conspecific specimens.

Discussions

MP data in water show a generally higher contamination in the sites located north than the ones located south in both surface and column water. The observed distribution is similar to the one obtained by the previous GdL campaigns in 2017 and 2018 (unpublished data ENEA-Legambiente), when northern sampling sites showed the highest contamination. As it was observed that wind is affecting the concentration of MPs in water in other volcanic lakes of Central Italy, namely Lake Bolsena and Lake Chiusi (Fischer et al. 2016), the action of wind and its direction from the south prevalent in Lake Bracciano during summer is the main explanation for the greater concentration of MPs.

Surface and column samplings differ significantly about the shape of MPs, fragments being more frequent than fibres in surface. The different distribution of MPs in the water column according to shape is also analysed in a recent study on a deep dimictic lake, Lake Tollense, where fragments are more abundant in surface than in water column (Tamminga and Fischer 2020). It is suggested that the action of wind is the cause of this uneven distribution as fibre floating or sinking is limitedly affected by wind-induced water circulation because of their linear shape. Instead, fragments accumulate on surface because they are more affected by water transport due to their larger surface exposed to currents (Tamminga and Fischer 2020). Further research needs to be conducted as scientific literature is lacking investigations on this topic.

The main polymers found in water are CPE and PE, which are among the main MPs found in fresh waters (Yang et al. 2022). Among the polymers found in water, two of them were also found in fish, specifically PS and PA. These two polymers are also found in other fish species worldwide, being among the most frequent polymers found (Cera et al. 2020).

As regards fish contamination by MPs, it was observed that the phenomenon of MPs ingestion was rare. It is possibly due to a combined effect of variable environmental contamination and location of fish sampling sites, which are not necessarily fished in the most contaminated areas of the

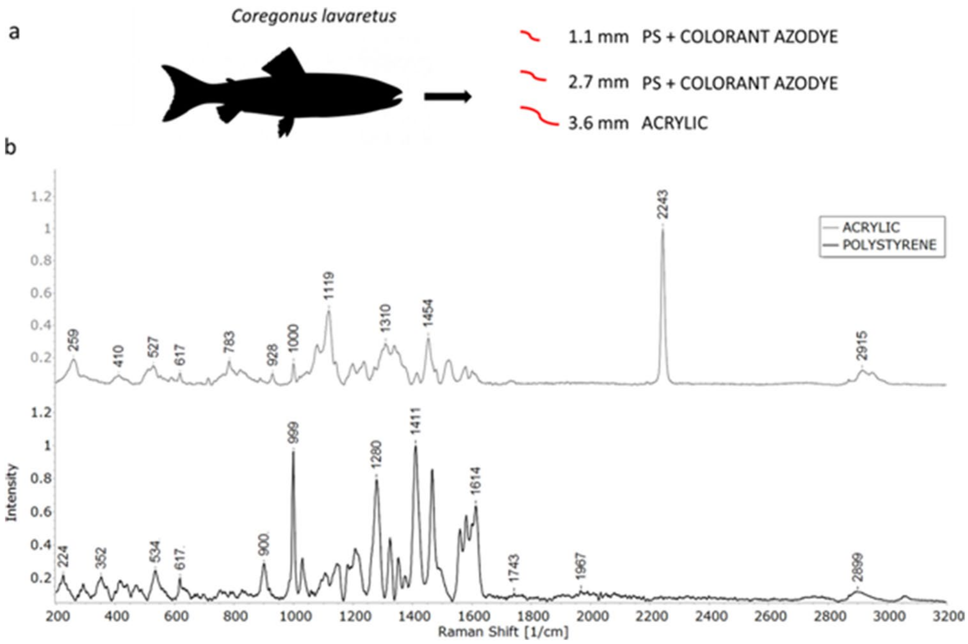

Fig. 5 **a** Contaminated fish specimens and length, and polymer type of each MPs detected. **b** Sample spectra of MP polymers obtained by 785 nm source, magnification 50×, 1–5% range of laser intensity, 10 s acquisition time, 1 accumulation. Spectra processed by smoothing and background, peaks removed. PS polystyrene

lake. The two species show different results of MPs ingestion. In detail, no *A. boyeri* ingested MPs in Lake Bracciano; conversely, one study reported that marine populations of *A. boyeri* can ingest MPs (Shabaka et al. 2020). In marine ecosystems, *A. boyeri* has a contamination generally lower than other marine species (Shabaka et al. 2020). As *A. boyeri* is able to ingest MPs, it is supposed that the absence of MPs in *A. boyeri* from Lake Bracciano could be affected by the fact that the GITs of the sampled specimen were mostly empty, inducing to support that the act of feeding is a factor influencing the ingestion of MPs (Peters and Bratton 2016). Indeed, it is proposed by scientific literature that the uptake of MPs can be accidental, for instance, it may occur while fish are feeding (Roch et al. 2020). Regarding *C. lavaretus*, all MPs found in its GIT were fibres, which are the most common shape of MPs found in column water rather than surface water, suggesting a stronger connection between fish contamination and water column contamination. A comparison with scientific literature shows that this is the first report of MP ingestion by *C. lavaretus*. However, another species of *Coregonus*, *C. wartmanni* (Bloch, 1784), is reported to have ingested MPs in Lake Costance (Roch et al. 2019). It was observed that *C. wartmanni* had higher abundance of MP ingested than the other sampled fish species (Roch et al. 2019). This observation and the results from this study could preliminarily suggest a higher probability of ingestion by these species compared to other species. If confirmed, that would imply that the genus *Coregonus* might provide an early warning signal for MP presence or abundancy. However, this topic needs further research due to limited information.

The different results between *A. boyeri* and *C. lavaretus* here discussed could be due to several factors, such as the presence of preys in the GITs, discussed above, or habitat preferences. As regards the habitat preferences, *A. boyeri*, which is a demersal species, is less contaminated than *C. lavaretus*, which is a pelagic species. Scientific literature on marine ecosystems assesses that pelagic species are more contaminated than demersal (Rummel et al. 2016; Yagi et al. 2022), and demersal-pelagic species (Neto et al. 2020). Although this study is carried out in a lentic ecosystem, the observations on the examined freshwater species confirm data from marine species, suggesting a similar ingestion pattern between the two systems. The possible factors explaining the prevalence of MPs in the GITs of pelagic species rather than in demersal ones are not fully clarified yet. However, it is suggested that as pelagic fish can feed at different depth strata, they can possibly find and ingest more MPs than demersal fish, which are limited to a certain depth (Neto et al. 2020).

This study investigated the concentration of MPs in the GITs of fish species of economic interests that are regularly consumed by human populations; therefore, it was questioned whether the presence of MPs could have repercussions in terms of food safety. As for *A. boyeri*, these specimens are usually consumed whole, so MPs in their GITs would also be eaten. *Atherina boyeri*, like other species eaten whole, for instance molluscs, are of great concern regarding food safety due to the direct transfer of MPs in the human gastrointestinal tract (Smith et al. 2018). However, no MPs were detected in *A. boyeri*'s GITs; hence, the risk can be considered not relevant to date based on the available information. Conversely, some MPs were detected in the GITs of *C. lavaretus*, although MP concentrations (0.15 MPs/fish) were low compared to the mean values observed in lake fish (5.50 MPs/fish) and in high-income economies (1.45 MPs/fish), according to a recent review (Zazouli et al. 2022). The GITs of *C. lavaretus* are discarded as fillets are the edible part; hence, there is no ingestion of the MPs from GITs during food consumption. Although the scientific literature highlights that MPs can be transferred into tissues (such as muscles) by the GIT, there is currently no study available that relates the MP concentration in fish GIT, fish fillets and negative impacts on human health. Therefore, there are no evidences of a risk to food safety caused by fish from Lake Bracciano.

Research examining simultaneous contamination of water and fish is scarce in lakes. In Italy, only one study carries out an investigation on this topic in a high mountain lake; however, no MPs were detected either in water or in fish (Pastorino et al. 2021). Based on the information from a recent review (Cera et al. 2020), only 4 articles can be found on this topic among 158 ones published on MPs in freshwaters from 2012 until 2020. Comparing the articles of interest to the total ones investigating MPs in lentic ecosystems (obtained from Cera et al. 2020), it is stunning how few are on this topic and that the growth is not as steep as the total one (Supplementary Information 4). In addition, after conducting a bibliographic search by Scopus and Web of Science search engines using the keywords “microplastic*” and “lake” and “fish”, two new articles published in 2021 were found, showing an increasing interest on analysing the relationship between water and fish contamination. Roch et al. (2019) is also added to the list of articles on this topic because it compares water and fish contamination, although water data was obtained by a survey conducted during fish sampling (Heß et al. 2018). Hence, the total number of articles investigating simultaneously the contamination of water and fish in lakes is 8, including this study (Table 1).

A quantitative and qualitative comparison between the observations from Lake Bracciano and the 7 studies collected by scientific literature was attempted. The quantitative comparison of the MPs concentration found in Lake Bracciano to lentic fresh waters worldwide is not carried out due to the lack of methodological standardisation. Nowadays, some methodological efforts are conducted

Table 1 Reference articles on contamination of lacustrine water and fish by MPs. *na* not available

Reference	Country	Site	MPs in water[1]	Units	Sampling method	#MPS/FISH[1]	# specimen sampled
Faure et al., (2012)	France and Switzerland	Lake Geneva	48,146 ± na	items/km^2	Manta net mesh 300 μm	0	41
Faure et al. (2015)	France and Switzerland	Lake Geneva (Grand Lac)	220,000 ± 160,000	items/km^2	Manta net mesh 300 μm	0.85 ± 4.90	40
		Lake Geneva (Petit Lac)	33,000 ± 46,000	items/km^2	Manta net mesh 300 μm		
Roch et al. (2019) (HEß et al. 2018 **for water)**	Germany, Austria and Switzerland	Lake Constance	11.33 ± 8.70	items/m^3	Manta net mesh 300 μm	0.2 ± 0.5 (northern site) 0.3 ± 0.6 (southern site)	331
Wu et al. (2021)	China	Dafangying Reservoir	18,620 ± 7,120	items/m^3	Steel sampler (depth 0–30 cm) mesh 50 μm	from 8.8 ± 4.14 to 51.3 ± 7.42[2]	39
Xiong et al. (2018)	China	Lake Qinghai	180,900 ± 229,533	items/km^2	Trawl net mesh 112 μm	5.4 ± 3.6	10
Xu et al. (2021)	China	Lake Gehu	6.33 ± 2.67 = 6,330 ± 2,670	items/l items/m^3	Pump (depth 0–20 cm)	10.7 ± na	30
Yuan et al. (2019)	China	Lake Poyang	19.5 ± na = 19,500 ± na	items/l items/m^3	Steel sampler (depth 1 m)	9.27 ± 5.37	11
This study	Italy	Lake Bracciano	0.76 ± 1.00	items/m^3	Plankton net mesh 80 μm (depth 50 m)	0.15 ± 0.67	56
			1.29 ± 1.59	items/m^3	Manta net mesh 300 μm		
			392,000 ± 416,000	items/km^2	Manta net mesh 300 μm		

[1] Mean value ± standard deviation

[2] Variation due to the species considered

to solve this issue, for instance the Blue Lakes project (LIFE18 GIE/IT/000813) conducted in Lake Bracciano. Conversely, a qualitative comparison of the outputs provided by these articles is discussed to provide an overview of the critical issues and knowledge gaps. Research on comparing simultaneous water and fish MPs contamination was conducted in Asian and European study areas, providing partial information on the global status. Considering the lake origins, no volcanic lake is examined, excluding Lake Bracciano. As MPs settling and resuspension is affected by water currents, the circular or subcircular shoreline and high depth of volcanic lakes possibly impact MP transport and deposition differently from other lakes, with a shallower bathymetry or inlets. Further research could investigate whether the lacustrine origin is a factor to take into account for providing information on MP contamination and possibly predict the distribution pattern. Moreover, future research could carry out more diachronic studies, as Lake Geneva is the only site sampled twice.

Regarding fish, different methods were used for the extraction of MPs from the GIT; the digestion and filtration before conducting a visual identification of MPs by stereomicroscope could allow detecting smaller items in fish GIT than visual observation only. Indeed, the digested samples generally have higher levels of MPs than the one directly observed by stereomicroscope. However, the results were obtained from different species (Supplementary Information 3) in different study areas so there is a high variability of parameters that could also have affected the outcome. Indeed, biological (e.g. GIT length and complexity of morphology) and ecological (e.g. habitat) characteristics of fish can influence the concentration of MPs (Collard et al. 2019; Jabeen et al. 2017).

Conclusion

This study analyses the contamination of surface and column water and fish gastrointestinal tracts in Lake Bracciano, providing novel information from a volcanic lake to contribute investigating this phenomenon in Italian lakes, which are currently poorly studied. To date, the water contamination in summer is occurring especially in the northern sector where it is also more variable compared to the southern sector. MPs have different prevalent shape if surface MPs or column MPs are considered. The former are mainly fragments while the latter are mainly fibres. We highlight that the spatial distribution pattern of MPs in the water of Lake Bracciano needs further investigation in order to define the factors influencing the transport routes of MPs and the precision of results.

A rare ingestion of MPs is observed in the gastrointestinal tracts of 56 fish belonging to two planktonic species in Lake Bracciano. Limited information from scientific literature prevents assessing precisely the environmental concentration of MPs needed to cause consistent ingestion. Therefore, further research is mandatory. In the future, the outputs of this research field could contribute to establishing risk thresholds for limiting fish contamination and managing MPs pollution.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-20403-x.

Acknowledgements The authors would like to thank the Regional Park “Parco Naturale Regionale di Bracciano e Martignano” and the technical staff of Goletta dei Laghi for MPs sampling campaign. We thank the professional fishermen of “Cooperativa pescatori di Bracciano” for their valuable support for fish sampling.

Author contribution Conceptualization: Alessandra Cera, Massimiliano Scalici, Maria Sighicelli; Methodology: Alessandra Cera, Massimiliano Scalici, Maria Sighicelli, Armida Sodo; Formal analysis and investigation: Alessandra Cera, Francesca Lecce, Patrizia Menegoni, Armida Sodo; Writing—original draft preparation: Alessandra Cera; Writing—review and editing: Alessandra Cera, Massimiliano Scalici, Maria Sighicelli, Armida Sodo; Funding acquisition: Massimiliano Scalici, Maria Sighicelli; Resources: Massimiliano Scalici, Maria Sighicelli, Armida Sodo; Supervision: Massimiliano Scalici, Maria Sighicelli.

Funding This investigation was supported by funds of Ministry of Education, University and Research for the base research individual activities, and by the Grant of Excellence Departments, MIUR-Italy (ARTICOLO 1, COMMI 314 – 337 LEGGE 232/2016).

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Andrade MC, Winemiller KO, Barbosa PS, Fortunati A, Chelazzi D, Cincinelli A, Giarrizzo T (2019) First account of plastic pollution impacting freshwater fishes in the Amazon: Ingestion of plastic debris by piranhas and other serrasalmids with diverse feeding habits. Environ Pollut 244:766–773. https://doi.org/10.1016/j.envpol.2018.10.088

Baccetti N, Bellucci V, Bernabei S, Bianco P, Braca G, Bussettini M, Cascone C, Ciccarese L, D’Antoni S, Grignetti A, Lastoria B, Mandrone S, Mariani S, Silli V, Venturelli S (2017) Analisys and evaluation of environmental status of Lake Bracciano in Summer 2017. ISPRA. (In Italian)

Barbanti L, Pompilio L, Ambrosetti W (1996) Morphometry and thermal stratification in Italian lakes. 2. The “Depth Ratio” as a predictive index of thermal structures. Mem Ist Ital Idrobiol 54:31–42

Barnes DKA, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. Philos Trans r Soc B Biol Sci 364:1985–1998. https://doi.org/10.1098/rstb.2008.0205

Blettler MCM, Abrial E, Khan FR, Sivri N, Espinola LA (2018) Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps. Water Res 143:416–424. https://doi.org/10.1016/j.watres.2018.06.015

Blue Lakes • No microplastics, Just Waves project LIFE18 GIE/IT/000813 [WWW Document], 2018. URL https://lifebluelakes.eu/, https://lifebluelakes.eu/

Bokobza L, Bruneel J-L, Couzi M (2015) Raman Spectra of carbon-based materials (from graphite to carbon black) and of some silicone composites. C 1, 77–94. https://doi.org/10.3390/c1010077

Castro-Castellon AT, Horton AA, Hughes JMR, Rampley C, Jeffers ES, Bussi G, Whitehead P (2021) Ecotoxicity of microplastics to freshwater biota: considering exposure and hazard across trophic levels. Sci Total Environ. 151638. https://doi.org/10.1016/j.scitotenv.2021.151638

Cera A, Scalici M (2021) Freshwater wild biota exposure to microplastics: a global perspective. Ecol Evol 11:9904–9916. https://doi.org/10.1002/ece3.7844

Cera A, Cesarini G, Scalici M (2020) Microplastics in freshwater: what is the news from the world? Diversity 12:276. https://doi.org/10.3390/d12070276

Cera A, Gallitelli L, Cesarini G, Scalici M (2022) Occurrence of microplastics in freshwater, in: Hashmi, M.Z. (Ed.), Microplastic pollution: environmental occurrence and treatment technologies, emerging contaminants and associated treatment technologies. Springer International Publishing. https://doi.org/10.1007/978-3-030-89220-3

Cheung PK, Hung PL, Fok L (2019) River microplastic contamination and dynamics upon a rainfall event in Hong Kong, China. Environ Process 6:253–264. https://doi.org/10.1007/s40710-018-0345-0

Collard F, Gasperi J, Gabrielsen GW, Tassin B (2019) Plastic particle ingestion by wild freshwater fish: a critical review. Environ Sci Technol 53:12974–12988. https://doi.org/10.1021/acs.est.9b03083

De Rita D, Di Filippo M, Rosa C (1996) Structural evolution of the Bracciano volcano-tectonic depression, Sabatini Volcanic District, Italy. Geol Soc Lond Spec Publl 110:225–236. https://doi.org/10.1144/GSL.SP.1996.110.01.17

Di Pippo F, Venezia C, Sighicelli M, Pietrelli L, Di Vito S, Nuglio S, Rossetti S (2020) Microplastic-associated biofilms in lentic Italian ecosystems. Water Res 187:116429. https://doi.org/10.1016/j.watres.2020.116429

European Commission. Joint Research Centre. Institute for Environment and Sustainability., MSFD Technical Subgroup on Marine Litter., 2013. Guidance on monitoring of marine litter in European seas. Publications Office, LU

Faure F, Demars C, Wieser O, Kunz M, de Alencastro LF, Faure F, Demars C, Wieser O, Kunz M, de Alencastro LF (2015) Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. Environ Chem 12:582–591. https://doi.org/10.1071/EN14218

Faure F, Corbaz M, Baecher H, Felippe L (2012) Pollution due to plastics and microplastics in Lake Geneva and in the Mediterranean Sea. Arch Sci. 7

Ferrara O, Vagaggini D, Margaritora FG (2002) Zooplankton abundance and diversity in Lake Bracciano, Latium. Italy J Limnol 61:169. https://doi.org/10.4081/jlimnol.2002.169

Ferreira GVB, Barletta M, Lima ARA (2019) Use of estuarine resources by top predator fishes. How do ecological patterns affect rates of contamination by microplastics? Sci Total Environ 655:292–304. https://doi.org/10.1016/j.scitotenv.2018.11.229

Ferreira-Rodríguez N, Pavel AB, Cogălniceanu D (2020) Integrating expert opinion and traditional ecological knowledge in invasive alien species management: Corbicula in Eastern Europe as a model. Biol Invasions. https://doi.org/10.1007/s10530-020-02420-4

Fischer EK, Paglialonga L, Czech E, Tamminga M (2016) Microplastic pollution in lakes and lake shoreline sediments – a case study on Lake Bolsena and Lake Chiusi (central Italy). Environ Pollut 213:648–657. https://doi.org/10.1016/j.envpol.2016.03.012

Free CM, Jensen OP, Mason SA, Eriksen M, Williamson NJ, Boldgiv B (2014) High-levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull 85:156–163. https://doi.org/10.1016/j.marpolbul.2014.06.001

Frias JPGL, Nesh R (2019) Microplastics: finding a consensus on the definition. Mar Pollut Bull 138:145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022

Galafassi S, Sighicelli M, Pusceddu A, Bettinetti R, Cau A, Temperini ME, Gillibert R, Ortolani M, Pietrelli L, Zaupa S, Volta P (2021) Microplastic pollution in perch (Perca fluviatilis, Linnaeus 1758) from Italian south-alpine lakes. Environ Pollut 288:117782. https://doi.org/10.1016/j.envpol.2021.117782

Gallitelli L, Cera A, Cesarini G, Pietrelli L, Scalici M (2021) Preliminary indoor evidences of microplastic effects on freshwater benthic macroinvertebrates. Sci Rep 11:720. https://doi.org/10.1038/s41598-020-80606-5

GESAMP (2016) Sources, fate and effects of microplastics in the marine environment: part two of a globalassessment. In: Kershaw PJ, Rochman CM (eds) IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the scientific aspects of marine environmental protection. Rep.Stud. GESAMP No. 93, p 220

GESAMP, 2019. Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean (Kershaw P.J., Turra A. and Galgani F. editors), (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, 130p.

Gilgault J, Halle AT, Baudrimont M, Pascal P-Y, Gauffre F, Phi T-L, El Hadri H, Grassl B, Reynaud S (2018) Current opinion: what is a nanoplastic? Environ Pollut 235:1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024

Gouin T (2020) Toward an improved understanding of the ingestion and trophic transfer of microplastic particles: critical review and implications for future research. Environ Toxicol Chem 39:1119–1137. https://doi.org/10.1002/etc.4718

Gregory MR (2009) Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos Trans r Soc B Biol Sci 364:2013–2025. https://doi.org/10.1098/rstb.2008.0265

Guo J, Huang X, Xiang L, Wang Y, Li Y, Li H, Cai Q, Mo C, Wong M (2020) Source, migration and toxicology of microplastics in soil. Environ Int 137:105263. https://doi.org/10.1016/j.envint.2019.105263

Heß M, Diehl P, Mayer J, Rahm H, Reifenhauser W, Stark W, Schwaiger J (2018) Mikroplastik in Binnengewässern Süd- und Westdeutschlands 86.

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 46(6):3060–3075. https://doi.org/10.1021/es2031505

Holland ER, Mallory ML, Shutler D (2016) Plastics and other anthropogenic debris in freshwater birds from Canada. Sci Total Environ 571:251–258. https://doi.org/10.1016/j.scitotenv.2016.07.158

Hurley R, Woodward J, Rothwell JJ (2018) Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat Geosci 11:251–257. https://doi.org/10.1038/s41561-018-0080-1

Jabeen K, Su L, Li J, Yang D, Tong C, Mu J, Shi H (2017) Microplastics and mesoplastics in fish from coastal and fresh waters of China. Environ Pollut 221:141–149. https://doi.org/10.1016/j.envpol.2016.11.055

Jesus MD, Zapelini C, Schiavetti A (2021) Can citizen science help delimit the geographical distribution of a species? the case of the Callistoctopus sp. ("eastern octopus") on the Brazilian coast. Ethnobiol Conserv 10. https://doi.org/10.15451/ec2020-09-10.03-1-15

Kataoka T, Nihei Y, Kudou K, Hinata H (2019) Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environ Pollut 244:958–965. https://doi.org/10.1016/j.envpol.2018.10.111

Katare Y, Singh P, Sankhla M, Singhal M, Jadhav EB, Parihar K, Nikalje BT, Trpathi A, Bhardwaj L (2022) Microplastics in aquatic environments: sources, ecotoxicity, detection & remediation. Biointerface Res Appl Chem. 12(3), 3407–3428. https://doi.org/10.33263/BRIAC123.34073428

Koelmans AA, Mohamed Nor NH, Hermsen E, Kooi M, Mintenig SM, De France J (2019) Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res 155:410–422. https://doi.org/10.1016/j.watres.2019.02.054

Kurniawan SB, Said NSM, Imron MF, Abdullah SRS (2021) Microplastic pollution in the environment: insight into emerging sources and potential threats. Environ Technol Innov 23:101790. https://doi.org/10.1016/j.eti.2021.101790

Lambert S, Wagner M (2018) Microplastics are contaminants of emerging concern in freshwater environments: an overview, in: Wagner, M., Lambert, S. (Eds.), Freshwater microplastics: emerging environmental contaminants?, The Handbook of Environmental Chemistry. Springer International Publishing, Cham, pp. 1–23. https://doi.org/10.1007/978-3-319-61615-5_1

Lusher AL, Bråte ILN, Munno K, Hurley RR, Welden NA (2020) Is it or isn't it: the importance of visual classification in microplastic characterization. Appl Spectrosc 74:1139–1153. https://doi.org/10.1177/0003702820930733

Margaritora FG, Bazzanti M, Ferrara O, Mastrantuono L, Seminara M, Vagaggini D (2003) Classification of the ecological status of volcanic lakes in Central Italy. J Limnol 62:49. https://doi.org/10.4081/jlimnol.2003.s1.49

Mazza R, Vigna FL, Capelli G, Dimasi M, Mancini M, Mastrorillo L (2015) Hydrogeology of Rome. Acque Sotter. - Ital. J. Groundw. 4. https://doi.org/10.7343/as-129-15-0156

Menges F (2020) Spectragryph - optical spectroscopy software v.1.2.15.

Ministero dell'ambiente e della tutela del territorio e del mare, 2007. Volcanic lakes, habitat series. Museo Friulano di Storia Naturale, Udine. (In Italian)

Munno K, De Frond H, O'Donnell B, Rochman CM (2020) Increasing the accessibility for characterizing microplastics: introducing new application-based and spectral libraries of plastic particles (SLoPP and SLoPP-E). Anal Chem 92:2443–2451. https://doi.org/10.1021/acs.analchem.9b03626

Neto JGB, Rodrigues FL, Ortega I, Rodrigues LDS, Lacerda ALDF, Coletto JL, Kessler F, Cardoso LG, Madureira L, Proietti MC (2020) Ingestion of plastic debris by commercially important marine fish in southeast-south Brazil. Environ Pollut 267:115508. https://doi.org/10.1016/j.envpol.2020.115508

Nicolosi I, D'AjelloCaracciolo F, Pignatelli A, Chiappini M (2019) Imaging the Bracciano caldera system by aeromagnetic data inversion (Sabatini Volcanic District, Central Italy). J Volcanol Geotherm Res 388:106680. https://doi.org/10.1016/j.jvolgeores.2019.106680

Pastorino P, Pizzul E, Bertoli M, Anselmi S, Kušće M, Menconi V, Prearo M, Renzi M (2021) First insights into plastic and microplastic occurrence in biotic and abiotic compartments, and snow from a high-mountain lake (Carnic Alps). Chemosphere 265:129121. https://doi.org/10.1016/j.chemosphere.2020.129121

Peters CA, Bratton SP (2016) Urbanization is a major influence on microplastic ingestion by sunfish in the Brazos River Basin, Central Texas, USA. Environ Pollut 210:380–387. https://doi.org/10.1016/j.envpol.2016.01.018

Piñon-Colin TDJ, Rodriguez-Jimenez R, Rogel-Hernandez E, Alvarez-Andrade A, Wakida FT (2020) Microplastics in stormwater runoff in a semiarid region, Tijuana, Mexico. Sci Total Environ 704:135411. https://doi.org/10.1016/j.scitotenv.2019.135411

Roch S, Walter T, Ittner LD, Friedrich C, Brinker A (2019) A systematic study of the microplastic burden in freshwater fishes of south-western Germany - are we searching at the right scale? Sci Total Environ 689:1001–1011. https://doi.org/10.1016/j.scitotenv.2019.06.404

Roch S, Friedrich C, Brinker A (2020) Uptake routes of microplastics in fishes: practical and theoretical approaches to test existing theories. Sci Rep 10:3896. https://doi.org/10.1038/s41598-020-60630-1

Rummel CD, Loder MGJ, Fricke NF, Lang T, Griebler E-M, Janke M, Gerdts G (2016) Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea. Mar. Pollut. Bull. 102(1), 134-141. https://doi.org/10.1016/j.marpolbul.2015.11.043

Ryan PG (2015) A brief history of marine litter research, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine anthropogenic litter. Springer International Publishing, Cham, pp. 1–25. https://doi.org/10.1007/978-3-319-16510-3_1

Schessl, M., Johns, C., Ashpole, S.L., 2019. Microbeads in sediment, Dreissenid mussels, and anurans in the littoral zone of the Upper St. Lawrence River, New York. Pollution 5. https://doi.org/10.22059/poll.2018.257596.468

Shabaka SH, Marey RS, Ghobashy M, Abushady AM, Ismail GA, Khairy HM (2020) Thermal analysis and enhanced visual technique for assessment of microplastics in fish from an Urban Harbor, Mediterranean Coast of Egypt. Mar Pollut Bull 159:111465. https://doi.org/10.1016/j.marpolbul.2020.111465

Sighicelli M, Pietrelli L, Lecce F, Iannilli V, Falconieri M, Coscia L, Di Vito S, Nuglio S, Zampetti G (2018) Microplastic pollution in the surface waters of Italian Subalpine Lakes. Environ Pollut 236:645–651. https://doi.org/10.1016/j.envpol.2018.02.008

Singh B, Sharma N (2008) Mechanistic implications of plastic degradation. Polym Degrad Stab 93:561–584. https://doi.org/10.1016/j.polymdegradstab.2007.11.008

Smith M, Love DC, Rochman CM, Neff RN (2018) Microplastics in seafood and the implications for human health. Curr Envir Health Rpt 5:375–386. https://doi.org/10.1007/s40572-018-0206-z

Stella E (1984) Fondamenti di Limnologia, Edizione dell'Ateneo. ed. Roma

Tamminga M, Fischer EK (2020) Microplastics in a deep, dimictic lake of the North German Plain with special regard to vertical distribution patterns. Environ Pollut 267:115507. https://doi.org/10.1016/j.envpol.2020.115507

Taviani S, Henriksen HJ (2015) The application of a groundwater/surface-water model to test the vulnerability of Bracciano Lake (near Rome, Italy) to climatic and water-use stresses. Hydrogeol J 23:1481–1498. https://doi.org/10.1007/s10040-015-1271-0

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science 304:838–838. https://doi.org/10.1126/science.1094559

Wang W, Ndungu AW, Li Z, Wang J (2017) Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci Total Environ 575:1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213

Wu J, Jiang Z, Liu Y, Zhao X, Liang Y, Lu W, Song J (2021) Microplastic contamination assessment in water and economic fishes in different trophic guilds from an urban water supply reservoir after flooding. J Environ Manage 299:113667. https://doi.org/10.1016/j.jenvman.2021.113667

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. Environ Pollut Barking Essex 1987(235):899–906. https://doi.org/10.1016/j.envpol.2017.12.081

Xu S, Ma J, Ji R, Pan K, Miao A-J (2020) Microplastics in aquatic environments: occurrence, accumulation, and biological effects. Sci Total Environ 703:134699. https://doi.org/10.1016/j.scitotenv.2019.134699

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. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-021-15338-8

Yagi M, Kobayashi T, Maruyama Y, Hoshina S, Masumi S, Aizawa I, Uchida J, Kinoshita T, Yamawaki N, Aoshima T, Morii Y, Shimizu K (2022) Microplastic pollution of commercial fishes from coastal and offshore waters in southwestern Japan. Mar Pollut Bull 174:113304. https://doi.org/10.1016/j.marpolbul.2021.113304

Yang S, Zhou M, Chen X, Hu L, Xu Y, Fu W, Li C (2022) A comparative review of microplastics in lake systems from different countries and regions. Chemosphere 286:131806. https://doi.org/10.1016/j.chemosphere.2021.131806

Yin L, Wen X, Du C, Jiang J, Wu L, Zhang Y, Hu Z, Hu S, Feng Z, Zhou Z, Long Y, Gu Q (2019) Comparison of the abundance of microplastics between rural and urban areas: a case study from East Dongting Lake. Chemosphere 244:125486. https://doi.org/10.1016/j.chemosphere.2019.125486

Yuan W, Liu X, Wang W, Di M, Wang J (2019) Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China. Ecotoxicol Environ Saf 170:180–187. https://doi.org/10.1016/j.ecoenv.2018.11.126

Zazouli M, Nejati H, Hashempour Y, Dehbandi R, Nam VT, Fakhri Y (2022) Occurrence of microplastics (MPs) in the gastrointestinal tract of fishes: a global review and meta-analysis and meta-regression. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.152743

Zhang K, Su J, Xiong X, Wu X, Wu C, Liu J (2016) Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. Environ Pollut 219:450–455. https://doi.org/10.1016/j.envpol.2016.05.048

Zhang Y, Kang S, Allen S, Allen D, Gao T, Sillanpää M (2020) Atmospheric microplastics: a review on current status and perspectives. Earth-Sci Rev 203:103118. https://doi.org/10.1016/j.earscirev.2020.103118

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