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MICROPLASTICS IN THE WATERS OF EUROPEAN LAKES AND THEIR POTENTIAL EFFECT ON FOOD WEBS: A REVIEW

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Abstract

Microplastics are widely distributed in aquatic environments. Studies to date have focused mainly on marine environments, and there is a substantial body of work in this topic. Contamination in freshwater ecosystems is a new and growing problem that has received decidedly less attention; this includes lakes that are particularly vulnerable because of their close proximity to emission sources. The first studies on the problem of lake microplastic pollution were not published until 2011, but interest among researchers has increased in recent years. The aim of this review is to assess the current state of knowledge about levels of microplastic pollution in European lake waters and to identify the most urgent areas of research that are required. A review of available data indicated that the number of lakes that have been investigated remains small in light of the overall number of lakes in Europe. The pollution levels in European lakes are similar to those in other lakes worldwide, but they are usually lower than those in marine ecosystems. There is a near total lack of data on the topic of the pollution of microplastics < 300 μm. This is a particularly significant gap in knowledge since some studies indicate that the quantity of microplastics in lakes might rise substantially if increasingly smaller particles are analyzed. Little attention is paid to the fate of microplastics in the water column and the influence they have on lake food webs. There is still no evidence confirming whether freshwater zooplankton ingest microplastics in their natural environments. However, the trophic transfer of microplastics in lake food webs is highly likely since microplastics have been confirmed in a wide range of freshwater ichthyofauna. Furthermore, there is a near total lack of multi-dimensional models that would describe the primary factors responsible for the accumulation of microplastics in lakes. Based on the present review, the most relevant recommendations are: developing a coherent research methodology that will facilitate comparing research results; assessing microplastic concentrations at various water column depths; increasing research on fine fractions of microplastics; identifying and estimating microplastic consumption rates by natural populations of aquatic organisms and assessing the risk of microplastic accumulation in food webs.

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Introduction

Initially, global attention focused on environmental pollution with larger plastic debris, but in recent years, researchers have come to focus on microplastics (GESAMP 2015). These are small plastic particles of various size, chemical composition, and physical properties. There is a lack of full consensus among researchers on how to define the term microplastic. The vast majority of researchers agree that microplastics include all synthetic polymer particles smaller than 5 mm (DUIS and COORS 2016). Some authors have also determined a lower limit for particle size. CLAESSENS et al. (2011) defined microplastics as particles ranging in size from 1 to 5 mm. The lower particle size limit is also sometimes defined as 0.1 μm (LUSHER et al. 2017a). Smaller particles known as nanoplastics range in size from 0.1 μm to 0.001 μm (KLAINE et al. 2012).

The shapes of polymer particles polluting the environment are varied, and the literature lacks cohesion with regard to the morphological description of the particles analyzed. Researchers have distinguished up to ten different particle shapes. HIDALGO-RUZ et al. (2012) distinguished the following shape categories of microplastics in the aquatic environment: filaments, films, foamed plastic, granules, fragments, pellets, and styrofoam. In terms of type, literature data indicate that the most frequently identified microplastic particles in aquatic ecosystems are polyethylene, polyethylene terephthalate, polypropylene, polystyrene, polyvinyl chloride, and, less frequently, polyamide (nylon), polyester, and acrylic (HIDALGO-RUZ et al. 2012, WAGNER et al. 2014).

Microplastic particles in surface waters originate from either primary or secondary sources. Primary microplastics reach the environment in the form in which they were manufactured. Polymer microgranules are used, inter alia, in personal care products such as toothpastes, gels, exfoliants, and many others. An estimated 1,500 metric tons of microplastics from personal care products are released annually into the global aquatic environment (SUN et al. 2020). Another source of primary microplastics is industrial abrasives that contain polystyrene, acrylic, melamine, polyester, and poly allyl diglycol carbonate microplastics (DUIS and COORS 2016). Primary microplastics also include pre-production granulates or regranulates that can be released into the environment accidentally during production, processing, storage, and transport (BOUCHER and FRIOT 2017). Primary microplastics are released into the aquatic environment with industrial wastewater, municipal wastewater, and in runoff from surfaces that are insufficiently secured during production or application. KARLSSON et al. (2018) estimated that wastewaters discharged daily into a stream near a Swedish plastic factory could carry from several to nearly one hundred thousand granules, which would mean a theoretical annual release of 73 to 730 kg of microplastics.

Although various sources of primary microplastics are identified in the literature, the annual global discharge of these microplastics has not yet been estimated. Thus, the significance of primary microplastic sources remains unknown as does the relative importance of primary and secondary sources (KOELMANS et al. 2014, BOUCHER and FRIOT 2017). It is presumed, however, that secondary microplastics are more widespread in the environment (COLE et al. 2011, EERKES-MEDRANO et al. 2015). Secondary microplastic environmental pollution is the product of macroplastic degradation that occurs mainly from mechanical factors and photodegradation. Microfibers generated by synthetic fabrics during daily use is currently the main source of microplastics in the environment (ACHARYA et al. 2021). Huge quantities of microfibers are released when laundering clothing in washing machines, and these are discharged with wastewaters from treatment facilities. The results of recent studies indicate that, depending on the type of clothing made of synthetic fibers that is laundered, one laundry cycle releases from 124 to 308 μg per kg of fabric laundered, and this corresponds to numbers of microfibers in the range of 640,000–1,500,000 (DE FALCO et al. 2019). Although the efficiency of retaining microfibers from wastewaters is currently high at treatment facilities, the sheer numbers of microfibers in wastewaters means that billions of these fibers are released into surface waters daily with discharged treated wastewaters.

Synthetic textile fibers are also released into the environment during the everyday use of fabrics (SUNDT et al. 2014). In addition to textiles, microplastics are generated during everyday household activities such as opening plastic packaging (SOBHANI et al. 2020) and by abrasion when using everyday plastic objects, and microplastics remain suspended in the air or settle as dust (MAGNUSSON et al. 2016). Secondary microplastics are generated outside, inter alia, by vehicle tire abrasion, which is a substantial source of environmental pollution (SOMMER et al. 2018). Other sources of secondary microplastics include synthetic polymer-based paints used in construction and road and ship paints that are released into the environment through mechanical abrasion or removal (DUIS and COORS 2016). Secondary microplastics form various sources are suspended in the atmosphere and deposited to aquatic ecosystems with precipitation. Secondary microplastics are also produced as the macroplastics littering surface waters and their vicinities degrade. Plastics can end up in aquatic environments from dumping and improper storage, but they can also be carried by winds and water runoff (MAGNUSSON et al. 2016). Water tourism and costal recreation are also sources of plastic refuse reaching the aquatic environment (THUSHARI and SENEVIRATHNA 2020).

Many studies focus on the problem of marine and oceanic microplastic pollution (e.g., MOOR et al. 2001, 2002, COLLINGTON et al. 2012, HIDALGO-RUZ et al. 2012, ISOBE et al. 2015), and the first data on the topic of the microplastic pollution of waters were published in the 1970s (CARPENTER and SMITH 1972). Studies of inland waters have not been conducted for nearly as long, and data regarding these waters are relatively few in comparison to those for seas and oceans (EERKES-MEDRANO et al. 2015, DUIS and COORS 2016). The first data on the topic of lake microplastic pollution was published just a decade ago (ZBYSZEWSKI and CORCORAN 2011). In this context, European lakes deserve special attention. Europe has close to 500,000 natural lakes with a surface area of at least 0.01 km^2. The highest concentrations of lakes are in the boreal and arctic regions. Most lakes are located in Norway, Sweden, Finland, and the Karelo-Kola Region of Russia. Water bodies in this area are usually characterized by large areas and perimeters. Many lakes are also located around the Baltic Sea in areas that were affected by the glacial period and in the northwestern part of the United Kingdom, Ireland, and Iceland. In central Europe, many lakes lie in mountain regions, including larger ones, which are located in Alpine valleys (European Environment Agency, VERPOORTER et al. 2014). European lakes are characterized by great diversity in terms of their origin, morphometry, trophic status, thermal regime, stratification, and water balance (BENGTSSON 2012). A basin's topography and water depth determine the variety of living organism communities it hosts. All the major physical zones of lakes and their associated fauna can be exposed to microplastics (Figure 1).

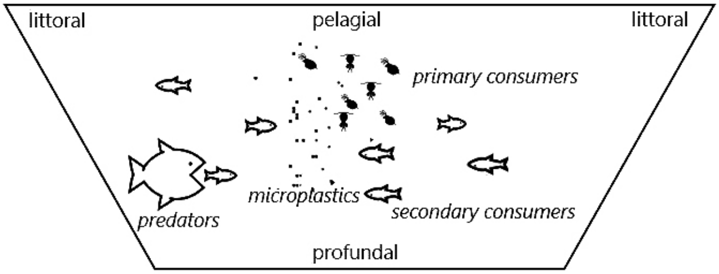

Fig. 1. Microplastics in a lake pelagial and their effect on local food webs

Microplastics in lake pelagic zones can be ingested intentionally or accidentally by primary consumers (zooplankton) or secondary consumers (fish) and transferred via the food web to higher trophic levels. In Europe the likelihood that surface waters are polluted with microplastics is very high because of the high population density and the high degree of industrialization (LEBRETON and ANDRARY 2019). Lakes are aquatic ecosystems that are particularly exposed to the accumulation of microplastics, and lakes that are fed by river waters are especially exposed since rivers are considered important vectors for transporting plastic pollution from the land to waters (LEBRETON et al. 2017). River waters flowing into lakes carry all types of pollution found in their catchments. Microplastics that are transported with river waters can be retained in lakes and can pose potential threats to the organisms inhabiting them and to humans. Many European lakes have important functions and serve as potable water reservoirs, water sources for aquaculture, and also recreational areas.

Microplastics are freshwater pollutants of emerging concern. The magnitude of microplastic pollution in European lakes is still unknown, and environmental risks have not yet been evaluated. We need complex data on microplastic concentrations, sources, and fates in freshwater ecosystems to assess their effects on lacustrine food webs and the responses of individuals or communities to exposure. To solve this the problem, it is essential to analyze existing research and identify current gaps in knowledge. Therefore, the aim of this article is to review the current state of knowledge of microplastic pollution in lake waters in Europe, the potential influence microplastics have on food web organisms in the water column that might be accidental microplastic consumers, and to identify areas that most urgently require research. It is hypothesized that:

– European lakes are polluted with microplastics, regardless of where they are located;
– fibers are a common form of microplastic that occurs in lakes;
– consumers in the pelagic food web might ingest microplastics.

Materials and Methods

In this review, microplastics are particles smaller than 5 mm without a lower size limit. The search for the articles required to review the state of knowledge was done in December 2021 (first two weeks) and January 2022 (twice weekly throughout the month) by searching ISI Web of Knowledge and Google Scholar. The key words and word combinations used in the search included microplastic(s), plastic, lake(s), fresh water, Europe, zooplankton, and fish. Of the records obtained, all those that were thematically relevant were used in the review.

Results and Discussion

Microplastics in the waters of European lakes

Although there are more than a half million lakes in Europe, few of them have been studied. The microplastic concentrations in the lakes studies were varied, but the analysis of data published by different authors indicated that there is a lack of consistent study methodology that makes it very difficult to compare and interpret results. While some researchers collected samples with manta nets, which only collect samples from the surface water layer, some used plankton nets, and still others used pumps to collect samples from the water column and concentrated them through sieves. Water samples were also collected with small, graded containers. The concentrations of microplastic particles were reported per unit of water surface of lakes (the surface are covered by the trawl was known) or volume of water (based on the total volume of trawled or sampled water), and depended on the gear used to collect the microplastics (Table 1). Other researchers (DUSAUCY et al., 2021) also noted methodological inconsistencies and identified an urgent need to develop common standards for microplastic sampling, sample handling, analysis, and the presentation of research results.

Varying levels of lake microplastic pollution were confirmed in southern European Alpine countries (Table 1) ranging from a mean of 0.011 items m^{-2} in Lake Zürich to 0.220 items m^{-2} in lakes Maggiore and Geneva (Grand Lac) in Switzerland (FAURE et al. 2015) and from 0.004 items m^{-2} in Lake Garda to 0.057 items m^{-2} in Lake Iseo in Italy (SIGHICELLI et al. 2018).

Table 1

Microplastics concentrations in waters of European lakes

Lakes	Microplastic concentrations	Size of analyzed microparticles [μm]	Sampling method	Dominant types of microplastics (shape; polymer type)
Lake Kallavesi, (Finland)	a) 0.27±0.18 (mean ± SD) items m^{-3} b) 1.8±2.3 (mean ± SD) items m^{-3} c) 12±17 (mean ± SD) items m^{-3} d) 155±73 (mean ± SD) items m^{-3}	a) > 333 b) > 300 c) 100–300 d) 20–100	a) surface waters (manta trawl) b) surface waters (pump) c) surface waters (pump) d) surface waters (pump)	fibers, fragments; polyethylene, polypropylene, polyethylene, terephthalate UURASJÄRVI et al. (2020)

cont. table 1

67 European lakes (30° of latitude)	0–7.3 (median = 0.28) items m^{-3}	> 310	surface waters (plankton net)	fibers, Tanentzap et al. (2021)
Lake Tollense (Germany)	19–22 items m^{-3}	> 63	water column 0–10 m (pump)	fibers irregular shape;
	29–50 items m^{-3}			mainly polyethylene, polypropylene, polyethylene, terephthalate, polyamide Tamminga and Fischer (2020)
Lake Sassolo (Switzerland)	$2.6 \cdot 10^3$ items m^{-3} (excluding fibers)	> 125	surface waters (sampling by means of a jar)	pellets, fragments, films; mainly polyethylene, polypropylene
	$2.6 \cdot 10^3$ items m^{-3} (excluding fibers)	> 125	the outlet of the lake (sampling by means of a jar)	pellets, fragments, films; mainly polyethylene, polypropylene Negrete Velasco et al. (2020)
Lake Bolsena (Italy)	0.21-4.08 items m^{-3}	> 300	surface waters (manta trawl)	fragments, fibers
Lake Chiusi (Italy)	0.48–2.82 items m^{-3}			Fischer et al. (2016)
Lake Dziekanowskie (Poland)	4.7 µg m^{-2}	> 20	surface waters (plankton net trawl)	fibers; mainly polyethylene terephthalate, polyurethane
Lake Kalwa (Poland)	4.4 µg m^{-2}			
Lake Majcz (Poland)	4.1 µg m^{-2}			Kaliszewicz et al. (2020)

cont. table 1

Lake Maggiore (Italy)	0.029±0.017–0.045 ± 0.013 (mean ± SD) items m^{-2}	> 300	surface waters (manta trawl)	fragments, balls, filaments; mainly polyethylene, polypropylene, expanded polystyrene
Lake Garda (Italy)	0.004 ± 0.0027 – 0.055 ± 0.029 (mean ± SD) items m^{-2}			fragments, balls, filaments; mainly polyethylene, polypropylene
Lake Iseo (Italy)	0.015 ± 0.011 – 0.057 ± 0.036 (mean ± SD) items m^{-2}			fragments, balls, filaments; mainly polyethylene, expanded polystyrene Sighicelli et al. (2018)
Lake Geneva (Grand Lac, Switzerland)	0.220 ± 0.160 (mean ± SD) items m^{-2}	> 300	surface waters (manta trawl)	fragments, foams, films, fibers; mainly polyethylene, polypropylene, polystyrene
Lake Geneva (Petit Lac, Switzerland)	0.033 ± 0.046 (mean ± SD) items m^{-2}			
Lake Constance, (Switzerland)	0.061 ± 0.012 (mean ± SD) items m^{-2}			
Lake Neuchâtel, (Switzerland)	0.061 ± 0.024 (mean ± SD) items m^{-2}			
Lake Maggiore (Switzerland)	0.220 ± 0.150 (mean ± SD) items m^{-2}			
Lake Zurich (Switzerland)	0.011 ± 0.002 (mean ± SD) items m^{-2}			
Lake Brienz (Switzerland)	0.036 ± 0.023 (mean ± SD) items m^{-2}			Faure et al. (2015)
Lake Geneva, (Switzerland)	0.048 items m^{-2}	> 300	surface waters (manta trawl)	different; only rough data are available Faure et al. (2012)

Samples were collected from these lakes with manta nets with a mesh size of 300 μm. Most of these lakes are in significantly urbanized catchments and are at high risk for microplastic pollution. In turn, FISCHER et al. (2016) determined the levels of microplastic pollution per cubic meter of water in the Italian lakes Bolsena and Chiusi that ranged from 0.21 to 4.08 items m^{-3} and from 0.48 to 2.82 items m^{-3}, respectively. Much higher microplastic concentrations of 2.6 10^3 items m^{-3} were confirmed in Lake Sassolo, in Switzerland (NEGRETE VELASCO et al. 2020). In contrast with the other Italian and Swiss lakes described above, Lake Sassolo is an isolated, alpine lake that is practically free of anthropogenic pressure. This suggests that the primary source of pollution could be the atmosphere, i.e., dust, aerosols, wet and dry atmospheric deposition, and snow. Synthetic fibers transported atmospherically are one of the most important sources of pollution in isolated areas (EVANGELIOU et al. 2020). Methodological differences must be borne in mind when interpreting the mean concentrations of microplastics in Lake Sassolo since the water samples were concentrated with sieves of a mesh size twice as small (125 μm) as those used in the study by FISCHER et al. (2016) – Table 1; thus, the results obtained for Lake Sassolo might have been partially the result of the greater selectivity of the microplastic sampling gear. Conversely, the results of certain studies suggest that lakes are dominated by a finer fraction of microplastics. This is illustrated well by UURASJÄRVI et al. (2020) who conducted research in Lake Kallavesi in Finland. When they concentrated water samples using a mesh of > 300 µm, the microplastic concentration was at a moderate value of 1.8 items m^{-3}, but when they used mesh with a selectivity range of 20–100 µm, the mean value was 155 items m^{-3}. This could indicate that microplastics that reach lakes degrade into increasingly smaller particles that accumulate. UURASJÄRVI et al. (2020) concluded that the risk of microplastic accumulation in Lake Kallavesi is highly likely since its surroundings are significantly urbanized.

The data available on the level of microplastic pollution in European lakes is supplemented by those from Central and Eastern Europe. KALISZEWICZ et al. (2020) studied Lake Dziekanowskie in central Poland and lakes Kalwa and Majcz in the northeast of the country with the assumption that they were exposed to different degrees or anthropogenic pressure. The first two lakes are in urban areas, while Lake Majcz is located far from human settlements. The levels of pollution in the three lakes were, nevertheless, similar and ranged from 4.1 µg m^{-2} in Lake Majcz to 4.7 µg m^{-2} in Lake Dziekanowskie. In turn, TAMMINGA and FISCHER (2020) determined the pollution level of Lake Tollense in Germany at 19–22 items m^{-3} for fibers and 29–50 items m^{-3} for other microplastics (Table 1).

The newest data from TANENTZAP et al. (2021) make an important contribution to research on the problem of the microplastic pollution of European lakes. These researchers studied 67 lakes in which microplastic particle concentrations ranged from 0 to 7.3 (median = 0.28) items m^{-3} (Table 1). The vast majority of the particles examined were of anthropogenic origin. The main research question in this study did not address monitoring pollution, but focused on the factors determining the levels of pollution, and this is the first study of this kind. The model showed that lakes in urban catchments are more exposed to microplastic accumulation since this is where there is high potential for microplastic emissions, high population density, and high waste production and wastewater discharge. In turn, lakes in forested catchments are less exposed to microplastic accumulation as are those with high biological degradation rates thanks to resident microbial communities that facilitate the degradation of inflowing pollution.

Attention should be drawn here to a fundamental gap in the existing data. In the vast majority of studies, water was sampled from lakes with nets of a mesh size of approximately 300 μm (Table 1), which means that the current state of knowledge is limited to the larger microplastic fraction. Studies conducted to date have omitted smaller particles that could be of particular significance in the functioning of inland aquatic ecosystems. Smaller-sized microplastic particles can, for example, be ingested by planktonic organisms, and this risk is greater the higher the concentrations of them are in waters. DUSAUCY et al. (2021) reached similar conclusions in their review of microplastic pollution of lakes worldwide.

In qualitative terms, the decided majority of microplastics in the lakes studied were fibers, mainly polyethylene or polypropylene. The primary source of surface water plastic fiber pollution is discharged wastewaters and precipitation. The latter factor could be responsible for polluting lakes that are distant from human settlements and not under direct anthropogenic pressure. The widespread detection of plastic microfibers in European lakes is also the result of the sampling methods researchers apply. In the decided majority of the studies cited in this review, the sampling methodology was based on collecting samples from the water surface layers of the lakes studied (Table 1). This means that the only synthetic polymers isolated from the environment were those that had a specific weight lower [<1 g cm^{-3}] than that of water (HIDALGO-RUZ et al. 2012), and that, consequently, floated on surface waters. This includes polyethylene and polypropylene polymers, which dominated the samples analyzed. Thus, these studies could have omitted synthetic polymer particles the specific weights of which were higher (>1 g cm^{-3}) than that of water (HIDALGO-RUZ et al.

2012), and could therefore be located at greater depths. This should be considered when interpreting the study results published in the literature, and this is why there is an urgent need to supplement existing studies with assessments of microplastic concentrations in the entire water column from the surface to the bottom.

Generally, the pollution levels in European lakes are similar to those in lakes in other parts of the world (Table 2). The average microplastic concentrations reported in the literature for lakes located outside of Europe range from 0.017 items m^{-2} in Lake Michigan (MASON et al. 2016) to 0.19 items m^{-2} in Lake Winnipeg (ANDERSON et al. 2017), while for the smaller fraction of microplastics (> 110 μm) it was 8.5 items m^{-2} in the Three Gorges Reservoir (ZHANG et al. 2015). The amount of pollution reported per cubic meter of water ranged from a mean of 0.9 items in lakes in the Pampean Region (ALFONSO et al. 2020) to $11 \cdot 10^3$ items in lakes from the West Siberian Plain (MALYGINA et al. 2021), while in this last study very high values were confirmed for nanoplastics, that are a very small size fraction ranging from 1 to 350 nm.

Table 2

Microplastic concentrations in lake water in selected locations worldwide

Study area	Mean concentration and analyzed particle size	Reference
America		
Laurentian Great Lakes (United States/Canada)	0.0425 items m^{-2} (> 330 μm)	ERIKSEN et al. (2013)
Lake Michigan (United States)	0.0173 items m^{-2} (> 330 μm)	MASON et al. (2016)
Lake Winnipeg (Canada)	0.1934 items m^{-2} (> 330 μm)	ANDERSON et al. (2017)
Nine lakes in the Pampean Region (Argentina)	0.9 ± 0.6 items m^{-3} (> 330 μm to 1 mm)	ALFONSO et al. (2020)
Asia		
Lake Hovsgol (Mongolia)	0.0203 items m^{-2} (> 330 μm)	FREE et al. (2014)
Three Gorges Reservoir (China)	8.4656 items m^{-2} (> 110 μm)	ZHANG et al. (2015)
Qinghai Lake (China)	0.1809 items m^{-2} (> 110 μm)	XIONG et al. (2018)
Six Lakes from West Siberian Plain (Russia)	$11 \cdot 10^3$ items m^{-3} (1–350nm)	MALYGINA et al. (2021)

Pollution concentrations in lakes, whether they are located in Europe or other places, are usually lower than those in seas and oceans (Table 3).

Table 3

Microplastic concentrations (examples) in marine water in different locations worldwide

Study area	Microplastic concentration	Reference
North Pacific Gyre	0.334 items m^{-2}	MOORE et al. (2001)
Northwestern Mediterranean Basin	0.116 items m^{-2}	COLLINGTON et al. (2012)
East Asian seas	1.7 items m^{-2}	ISOBE et al. (2015)
Pacific Ocean (California coast)	approx. 8 items m^{-3}	MOORE et al. (2002)
Different localities	0–8 (700 items m^{-3})	HIDALGO-RUZ et al. (2012)
Northeastern Pacific Ocean and coastal British Columbia	8–9 (810 items m^{-3}) (mean: 2 080)	DESFORGES et al. 2015
Nearshore and offshore Goeje Island, southern Korea	195 ·10^{3} items m^{-3} (mean)	SONG et al. (2015)
Southern Ocean	0.003–0.09 items m^{-3}	ISOBE et al. (2017)
Guanabara bay, Rio de Janeiro, Brazil	1.40–21.3 items m^{-3}	GLAUCIA et al. (2019)

Examples of mean values describing the level of microplastic pollution in the marine environment reported in the literature ranged from approximately 0.2 items m^{-2} in the Mediterranean Sea (COLLINGTON et al. 2012) to nearly 2.0 items m^{-2} in the area of the East Asian seas (ISOBE et al. 2015). In the North Pacific Gyre, within which drifts the great Pacific garbage patch, microplastic pollution reached a level of 0.334 items m^{-2} (MOORE et al. 2001). Results per cubic meter of water differed significantly in various locations; relatively low microplastic concentrations (0.003–0.09 items m^{-3}) were reported in the Southern Ocean near Antarctica (ISOBE et al. 2017), that were even lower than those of many lakes. In most cases, pollution in seas and oceans was higher than that of lakes and ranged from several to several tens of items m^{-3} (MOOR et al. 2002, OLIVATTO et al. 2019) to as much as several tens of thousands of items m^{-3} (SONG et al. 2015). As with the results of studies on lakes, care should be taken when comparing the results of various researchers because of differences in the methodologies applied in studies. Microplastic concentrations in seas and oceans are, however, higher than those in lakes since they are the final recipients of terrestrial pollutants, and deep marine waters are considered to be major sinks for microplastic debris (WOODALL et al. 2014).

Potential impact of microplastic accumulation in lake waters on food webs

Since microplastics have different weights, they occur at different depths in lake waters. Even polyethylene and polypropylene fibers, which are common in lakes, floating on the surface can become covered with plastic spheres, which are diverse microbial communities of heterotrophs, autotrophs, predators, and symbionts (ZETTLER et al. 2013). This increases the weight of particles and displaces them to deeper water layers. The different depths at which microplastic particles pollute the water column means that they can threaten a wide spectrum of living organisms. The heaviest microplastic particles sediment, which can eliminate them temporarily or permanently from the water column.

The current state of knowledge on microplastic concentrations in lake waters indicates that the quantity of microplastics in the water column increases substantially the smaller the particles analyzed are. This means that limnic environments are dominated by microplastic particles that, because of their small sizes, can directly threaten organisms of smaller body sizes, which are mainly aquatic invertebrates. In the water column, invertebrate zooplankton form assemblages with a wide spectrum of species that includes many filter feeders. Planktonic organisms are the primary consumer link in the food chain, and by the passive ingestion of microplastics suspended in the water, they can include them into the food web. While the literature lacks data that confirm freshwater species ingest microplastics in their natural environments, some studies document freshwater zooplankton species ingesting microplastics under laboratory conditions. In studies of the influence of microplastics on freshwater zooplankton, selected species were exposed to microplastic particles under laboratory conditions. IMHOFF et al. (2013) exposed the freshwater cladoceran *Daphnia magna* to microplastics (polymethyl methacrylate 29.5±26 μm) and reported that the plastic was present in the digestive tracts of all specimens exposed, which indicates there is a risk of bioaccumulation in the food web. JEMEC et al. (2016) documented *D. magna* ingesting microplastic fibers from a commercial polyethylene terephthalate (PET) fleece textile consisting of fibers 20 μm thick. Most of the fibers *D. magna* ingested were approximately 300 μm long, but very large, twisted synthetic polymer fibers of approximately 1,400 μm were found in the intestines of some specimens. Microplastic fiber ingestion caused higher mortality among *D. magna*.

However, fluorescent plastic granules have been used in many studies of the ecology of freshwater zooplankton to determine, inter alia, the filtration rates of different zooplankton species. These experiments are indirect proof that spherical microplastics ranging in size from several to several tens of micrometers are ingested widely by various species of freshwater zooplankton mainly *Cladocera* and *Rotifera*, while some *Copepoda* avoided plastic microgranules (e.g., AGASILD and NÕGES 2005). Considering the possible selectivity of different species regarding varied microplastic forms and shapes in the environment, environmental studies must be continued. This is especially true given the inherent weakness in laboratory studies that prevents results from being extrapolated to natural conditions, which is that the microplastic concentrations to which zooplankton were exposed in the studies above exceeded the concentrations of synthetic polymers noted in lakes under natural conditions.

Some information on possible freshwater zooplankton ingestion of microplastics under natural conditions and the consequences of this is provided by studies of the marine environment, which are more advanced on this topic. Many studies have proved that under natural conditions various zooplankton species ingest microplastics that pollute marine waters (BOTTERELL et al. 2019). Zooplankton microplastic ingestion results in shorter or longer retentions times in organisms. Some particles are excreted without causing harm to organisms; however, even after excretion these feces tend to stick to carapaces meaning that organisms remain sources of microplastic contamination for potential consumers (COLE et al. 2013). Ingesting microplastic was fatal in some specimens, while others survived but ingested microplastics were retained in digestive tracts (BOTTERELL et al. 2019). Microplastic retention in the zooplankton trophic level could cause these pollutants to be incorporated into aquatic ecosystem food webs. Fish foraging on zooplankton are exposed to the indirect ingestion of synthetic polymer particles. DESFORGES et al. (2015) presented interesting results of their assessment of the microplastic ingestion of various zooplankton species in the marine environment concluding that synthetic polymers were present in 1 item per 34 copepods and 1 item per 17 euphausiids. Further, they estimated that zooplankton containing microplastics would lead to juvenile salmon and returning adult individuals in coastal British Columbia ingesting 2–7 microplastic items per day and approximately 90 microplastic particles per day, respectively. Thus, seemingly low zooplankton microplastic ingestion can cause significant accumulation of pollutants in subsequent trophic levels of the food web.

Ample evidence in the literature suggests that fishes ingest microplastics. CERA and SCALICI (2021) summarized the state of knowledge to date on this topic and reported that microplastics were confirmed in 135 freshwater ichthyofauna species and that microplastic contamination was also confirmed in fishes from lakes in Europe. KUŚMIEREK and POPIOŁEK (2020) confirmed microplastics in the digestive tracts of approximately half of 400 common roach and gudgeon specimens caught upstream and downstream from Lake Michalice dam reservoir in southern Poland. ROCH et al. (2019) examined 22 fish species from lakes and rivers in southern Germany and reported that approximately a fifth of specimens examined had ingested microplastics. In turn, microplastics were confirmed in the digestive tracts of 7.5% of fishes examined from Lake Geneva (FAURE et al. 2015). These studies suggest that the degree of microplastic pollution in inland waters might determine the amount of pollution ichthyofauna ingest. PETERS and BRATTON (2016) confirmed that the microplastic content in the natural environment was positively correlated with fish ingesting it. In addition to the availability of microplastics in the environment, other factors can influence the quantities in which ichthyofauna ingest them including foraging strategies, trophic transfer (consumption of prey contaminated by microplastics), energy requirements, and individual specimen sizes. For example, larger roach were more likely to ingest the maximum possible number of available microplastic particles than were smaller fish (HORTON et al. 2018).

The effects of microplastic ingestion by fishes are varied. Negative effects of microplastic ingestion that have been observed in fishes include, inter alia, changes in swimming behavior (QIANG and CHENG 2019), limited growth and survival (NAIDOO and GLASSOM 2019), oxidative stress and changes in blood biochemistry (HATAMI et al. 2019), and disadvantageous endocrinological effects and reproductive disturbances (ROCHMAN et al. 2014), while nanoplastics, the smallest fraction, can cross the blood-brain barrier, which is highly selective in vertebrates, causing brain damage and behavioral changes (MATTSSON et al. 2017).

Microplastic migration through trophic levels of the food web could indirectly threaten humans through their diets. Not only could fish species sold commercially be contaminated (SANTILLO et al. 2017), so too could fish meal used in the manufacture of fodder for aquaculture and animal husbandry (THIELE et al. 2020). Inland waters are also often reservoirs of potable water and their contamination with microplastics should also be cause for concern with regard to human health (KOELMANS et al. 2019). Currently, according to the FAO (LUSHER et al. 2017b), the current state of the knowledge on microplastic particle toxicity indicates, that the risks associated with the consumption of fisheries and aquaculture products contaminated with microplastics is negligible in comparison with the benefits of consuming them. In their report, however, the FAO underscored the necessity of continuing research on polymer toxicity and that preventive and mitigation strategies must be implemented in the management of environmental plastic pollution.

Conclusions

Microplastics were recorded in all the European lakes that were investigated. However, considering the numerous lakes in Europe, their vast diversity, and the population density of the continent, the breadth of knowledge of European lake pollution remains insufficient. First, coherent research methodology must be developed that will foster comparing research results. Additionally, despite the growing number of studies of microplastics in European lakes, there is still insufficient information regarding the size fraction smaller than 300 µm, which is particularly important since the quantities of microplastics in water increase significantly as the size of these particles decreases. It is also necessary to supplement the state of the knowledge to date on microplastic concentrations in deeper water layers, because most studies focused only on surface water layers. Further, there are almost no multi-dimensional models describing the primary factors that are responsible for the accumulation of microplastics in lakes. To date, hydrological conditions, lake mixing regimes, and many other factors that could potentially affect microplastic retention levels in the water column have yet to be investigated. Information is also lacking on natural populations of zooplankton potentially ingesting microplastics and the effects of this, which is particularly important when these planktonic organisms are the foundation of the food web since any factor that poses a risk to this trophic level also threatens the functioning of entire lake ecosystems. Trophic transfer of microplastics in lake food webs is highly likely since microplastics were confirmed in wide range of freshwater ichthyofauna.

Considering the fact that only 85 lakes of over 500,000 European lakes (> 0.01 km^2) were investigated, further studies are necessary. Expanding research on microplastics in lakes will permit fully assessing the degree of environmental threat the presence of microplastics in lake waters poses to both the organisms inhabiting them and to humans. Based on the current state of the science, the following must be done:

– develop a consistent methodology for microplastic collection and sample analysis;

– increase the range of lakes monitored for microplastic pollution;

– assess microplastic concentrations in various layers of the water column from the surface to the bottom;

– increase research on the fine fraction of microplastics (< 300 um);

– identify and estimate microplastic consumption rates of natural populations of aquatic organisms and assess the risk of microplastic accumulation in food webs.

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