PAN POLSKA AKADEMIA NAUK
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.156054
2025, No. 67 (X–XII): 215–230

Microplastics in Polish freshwater ecosystems: Current state of knowledge and research gaps

Piotr Zieliński*[1)], Karolina Mierzyńska[2)]

[1)] University of Bialystok, Faculty of Biology, Department of Water Ecology, Ciołkowskiego 1J, 15-245 Białystok, Poland
[2)] Doctoral School of the University of Bialystok, Ciołkowskiego 1K, 15-245 Białystok, Poland

* Corresponding author

RECEIVED 12.06.2025 ACCEPTED 23.09.2025 AVAILABLE ONLINE 30.12.2025

Abstract: Microplastics (MPs, <5 mm) have been detected since the 1970s in various environments, including freshwater ecosystems. This review compiles and compares data on MPs in surface waters in Poland based on studies published up to 2024. In total, 65 aquatic ecosystems were analysed: 47 lakes, 13 rivers, and 5 dam reservoirs. Most Polish studies focused on MPs in water (73%), with fewer addressing bottom sediments (14%) or shoreline sediments (9%). Only 4% examined both water and bottom sediments simultaneously. The level of MP contamination varied widely, from 0 to 245,000 MP·m^{-3} in water and from 4 to 120,000 MP·kg^{-1} dry mass in sediments, with 11.5 MP per sample in riverine shoreline sediments. The highest levels occurred in rivers, particularly the Nida and Vistula. Identified particles differed in shape (mainly fragments and fibres), size (most often <1 mm), and colour (predominantly red, blue, and black). Considerable variation in analytical methods was observed, hindering direct comparison of results and highlighting the need for methodological standardisation. Given the heterogeneity of aquatic environments in Poland, further research on MPs is essential. Careful selection of study sites will help identify critical contamination hotspots more efficiently. Such an approach is necessary to develop effective mitigation strategies and protect Poland's freshwater resources from further deterioration of microplastic pollution.

Keywords: freshwater, lake, microplastic, pollution, river, sediment

INTRODUCTION

Plastic is a commonly used term for synthetic materials produced from fossil fuels through polymerisation, which does not naturally occur in the environment. The first breakthrough synthetic plastic was Bakelite, created in 1907 by Leo Hendrik Baekeland (Chalmin, 2019). Plastics are characterised by their lightness, water resistance, thermal and electrical insulation properties, resistance to many chemical factors, ease of processing, and low cost, making them widely used. From 1950 globally, more than 9,200 million metric tons (Mt) of virgin plastic have been produced (Islam and Khan, 2024), but less than 10% has been recycled (Dokl *et al.*, 2024). The remaining majority has been either landfilled, incinerated, or released into the environment through uncontrolled ways (Chen H. *et al.*, 2024). Today, plastics are produced on a massive scale and utilised worldwide (Thompson *et al.*, 2009; Thompson *et al.*, 2024). The global plastics production reached 413.8 Mt in 2023 (Plastics Europe AISBL, 2024), and recent estimates indicate that more than 170 · 10^{18} MP particles are floating in the world's oceans, with their total mass exceeding 2.3 Mt (Eriksen *et al.*, 2023). In 2023, around 2.4 Mt of plastics were produced in Poland, equivalent to 4.1% of Europe's overall production. It is estimated that 2.1 million tonnes of plastic waste were collected in Poland. Of this amount, 21% was recycled, 35% was used for energy recovery, and nearly 44% was landfilled (Plastics Europe Poland Foundation, no date). This means that the waste was sent to disposal sites, contributing to long-term environmental burden and the gradual release of plastic residues. While the volume of plastic waste directed to recycling has been gradually increasing, the rate of this growth remains significantly lower than the average observed across the European Union. These data indicate that the environmental risk associated with plastic pollution in Poland remains considerable. In recent years, the topic of plastic has been widely discussed and studied due to increasing reports on its ecological impact on water and terrestrial ecosystems and organisms at all levels of biological complexity – from single-celled to highly organised multicellular species (Plastics Europe Poland Foundation, no date).

Plastic materials, over time and under the influence of various external factors, break down into smaller fragments known as microplastics (MPs) – small discreet objects <5 mm in diameter (Arthur, Baker and Bamford, 2009) that is solid, insoluble in water and is partially or wholly composed of synthetic polymers or chemically modified natural polymers (EC, 2024). Particles of MPs present in aquatic environments can be classified as primary or secondary polymers. Primary MPs are purposely manufactured to fulfil a function (GESAMP, 2019), and are used in products such as cosmetics, polishing agents, and abrasives. Secondary MPs resulting from wear and tear or fragmentation of larger plastic objects (macro-, mesoplastics) (GESAMP, 2019) due to environmental factors such as UV radiation, thermal and mechanical abrasion, or biological degradation (Arif *et al.*, 2024). The first reports of MPs presence in the environment appeared in the 1970s (Carpenter and Smith, 1972), and most early research focused on marine and oceanic environments (Buchanan, 1971; Colton Jr, Burns and Knapp, 1974). In later years, MPs were also detected in the air (Dris *et al.*, 2016), soil (Büks and Kaupenjohann, 2020), and freshwater bodies (Horton *et al.*, 2017). Studies have shown that MPs occur even in extreme environments, ranging from ocean trenches (Peng *et al.*, 2018) and groundwater systems (Panno *et al.*, 2019; Tarasewicz *et al.*, 2025) to mountain peaks (Allen *et al.*, 2019) and Arctic ecosystems (Bergmann *et al.*, 2019).

Current literature identifies lotic waters as the primary source of MPs in oceans, leading to an increasing number of studies on this topic (Lebreton *et al.*, 2017). Due to the durability of synthetic polymers and the practically impossible removal of MP from the environment, another crucial aspect is the deposition of MPs in the bottom sediments (Waldschläger *et al.*, 2022). Microplastics are likely to have more lasting and serious environmental impacts than larger plastic debris (Souza Machado de *et al.*, 2018). The presence of MPs in aquatic environments poses several threats. Due to their size, they can be mistaken by zooplankton and ingested as bacterio- or phytoplankton (Cole *et al.*, 2013). This way, they enter food webs and undergo biomagnification, ultimately reaching the human diet (Cox *et al.*, 2019). Studies have shown that MPs, due to their high surface-to-volume ratio and hydrophobic properties, can absorb toxic substances such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dichlorodiphenyltrichloroethane (DDT) (Asim *et al.*, 2024). Since they are not fully excreted from organisms, they accumulate in their tissues (Fontes *et al.*, 2024).

The numerous negative effects of MPs pollution on the aquatic ecosystems (Dusaucy *et al.*, 2021; Pol *et al.*, 2023a) and organisms (Piskuła and Astel, 2022; Zolotova *et al.*, 2022) raise many questions regarding the extent of environmental contamination. Attempts to compare the level of MPs pollution in freshwater ecosystems have already been undertaken in various regions (Liu *et al.*, 2021; Gong *et al.*, 2023) and countries, including Germany (Schmidt *et al.*, 2020), China (Zhang *et al.*, 2018) Brazil (Castro, Silva da and Araújo de, 2018). This study presents a comparison of research on MPs pollution in Polish freshwater bodies published up to the end of 2024, which allows for defining the scale of the MPs problem in the Central Europe. We aim to assess the scope of existing analyses of MPs in freshwater bodies, in water, bottom, and shoreline sediments, as well as to identify the most commonly used methodologies and related challenges. Additionally, it highlights the key research gaps and outlines future directions for MPs studies in Poland. It also identifies legal shortcomings in national regulations concerning plastic waste management as well as environmental assessment frameworks that account for MPs.

MATERIALS AND METHODS

The literature review was conducted using the Web of Science and Google Scholar databases in April 2025, with the search restricted to publications published up to the end of 2024. The initial stage of the search involved the keywords "microplastics", "river", "lake", "dam reservoir" and "Poland," which were applied to titles, abstracts, keywords, and author affiliations. The retrieved publications were subsequently screened, and only those addressing MP pollution in inland waters were included. Studies had to consider contamination of water, bottom, and shoreline sediments to be eligible for inclusion. A complete list of the selected publications is presented in Table 1 and supplementary materials Table S1. In total, 22 publications were identified and analysed in terms of the spatial, quantitative, and qualitative characteristics of MPs in Poland.

Data on MP concentrations from selected publications were extracted and compiled into a dataset for statistical analysis (Tab. S1). In cases where data originated from the same site, e.g., the Vistula River, but were collected by different researchers at different times or sampling locations, were treated as separate records. In total, 65 different aquatic environments were identified, including 47 lakes, 13 rivers, and 5 dam reservoirs. Regarding the media analysed, 72 data entries concerned water samples, 11 referred to bottom sediments, and 3 to shoreline sediments. It is worth noting that in one river, concentrations of MP were simultaneously assessed in both water and bottom sediments across three sampling sites. To ensure data comparability, all results were converted to a common unit of MP particles per cubic meter ($MP{\cdot}m^{-3}$) for water and particles per kg ($MP{\cdot}kg^{-1}$) for bottom sediments. Due to the limited availability and comparability of data on qualitative analyses of MPs, descriptions of shapes, sizes, colours, and polymer types were based directly on source information. Statistical analyses on MP concentrations were performed using Statistica v. 13.3 (TIBCO Software Inc.).

RESULTS AND DISCUSSION

CHRONOLOGY OF MPS RESEARCH IN FRESHWATER ECOSYSTEMS IN POLAND

The first studies on MPs in aquatic ecosystems in Poland were conducted in 2016 and published a year later by Zima, Wielgat and Cysewski (2017) (Fig. 1). These early investigations focused on the presence of MPs in the water of the lower Vistula River (North Poland in Tczew). This was only slightly later than when

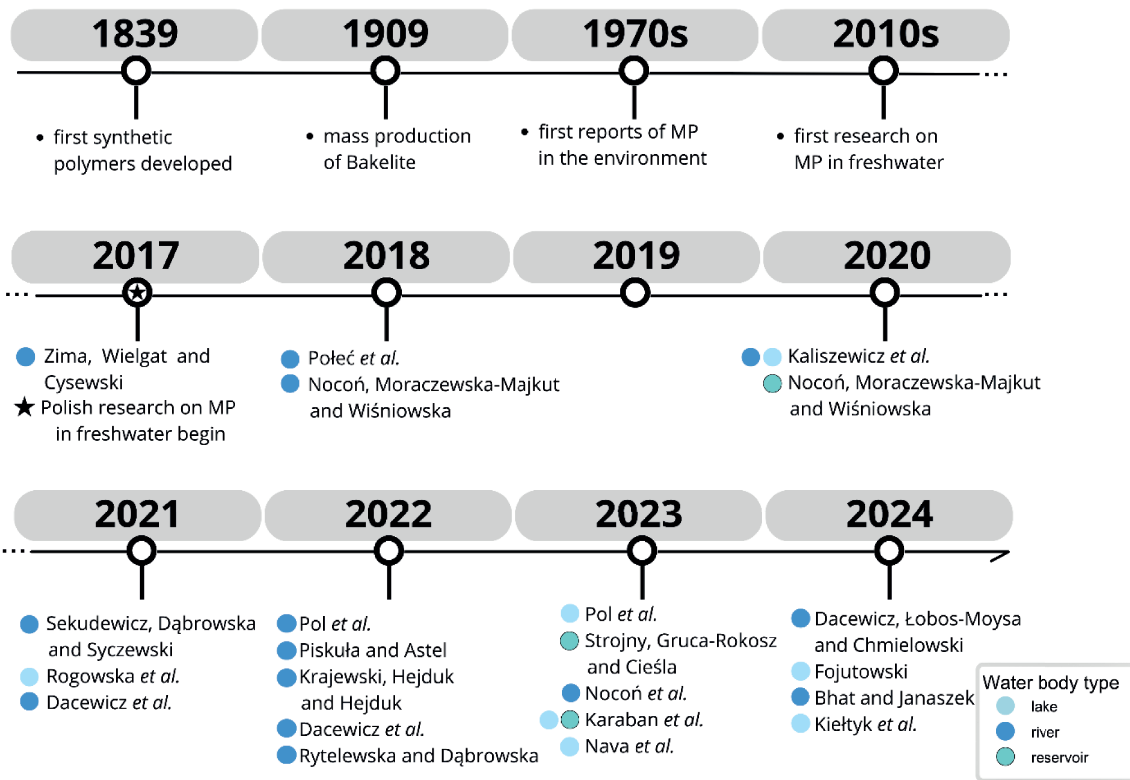

Fig. 1. Timeline of microplastics (MPs) study in Polish freshwaters in the context of global plastic production and MPs research history; source: own study

similar studies began to emerge in inland waters globally (Eriksen *et al.*, 2013; Dris *et al.*, 2015; Mani *et al.*, 2015). The first reports on MPs in bottom sediments come also from the section of the Vistula River (Central Poland, Warsaw) (Sekudewicz, Dąbrowska and Syczewski, 2021). The first findings concerning shoreline sediments also refer to the Vistula River and Wilanówka River in Warsaw, as documented by Rytelewska and Dąbrowska (2022). Research on MPs in both water and shoreline sediments of lakes began in 2019 and was later published by Rogowska *et al.* (2021) and Pol *et al.* (2023a), respectively. It is worth noting that the number of such studies has been gradually increasing, with the highest research activity observed in the past three years (Fig. 1). A very similar trend can be seen with the steadily growing interest in MPs research in surface waters worldwide, and the number of publications has been increasing almost exponentially in recent years (Gao *et al.*, 2024).

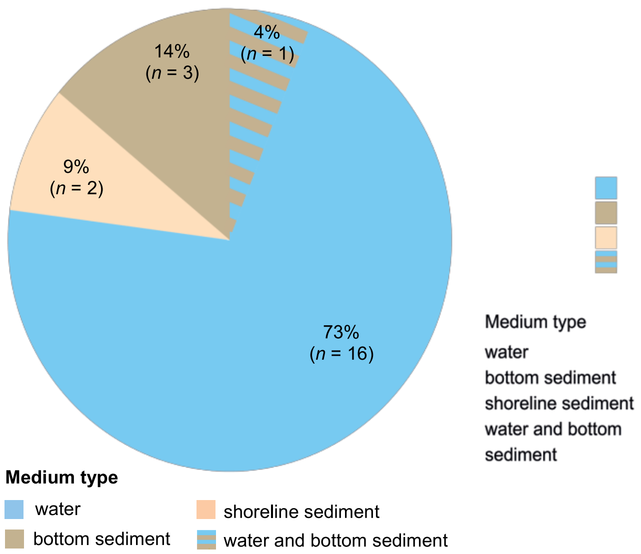

Fig. 2. Categorisation of publications on microplastics in Polish surface waters by medium type, based on studies published up to the end of 2024; source: own study

RANGE OF RESEARCH AND TYPES OF AQUATIC ECOSYSTEMS INVOLVED IN THE MICROPLASTICS STUDIES

The majority of studies on MPs contamination of Polish aquatic environments were focused on water samples (73%), highlighting a predominant interest. Bottom sediments-related studies accounted for 14%, while 9% of the publications investigated shoreline sediments (Fig. 2). A smaller fraction, only one publication (4%), examined MPs in both water and bottom sediment samples simultaneously. These findings indicate that while water samples have received the most MPs research attention, studies integrating multiple environmental matrices remain limited. Expanding future research to include bottom sediments and combined water-bottom sediment interactions would provide a more comprehensive understanding of MPs pollution in Polish surface waters. The significant disparity in research on MPs in water versus different sediments can largely be attributed to methodological differences in MPs isolation. Analysis of MP in water is definitely simpler and less labour-intensive than isolation from bottom sediments. Moreover, bottom sediment sampling itself requires more advanced equipment and a certain level of scientific experience. Numerous studies conducted worldwide highlight an increasing research focus on MPs in bottom sediments, due to their potential sites of accumulation, transport, degradation, and biochemical interactions. Similar patterns have been observed in numerous review studies concerning MPs in water, bottom and shoreline sediments across various aquatic environments (Yang *et al.*, 2022; Chen D. *et al.*, 2024; Gao *et al.*, 2024).

Studies on MPs in Polish surface waters have been conducted across 65 unique water bodies, including 47 lakes, 13 rivers, and 5 dam reservoirs (Fig. 3). The majority of research has focused on lakes, reflecting their significance in Poland's hydrological landscape and potential as sinks for MPs pollution (Dusaucy *et al.*, 2021). Due to the dominance of lakes in the landscape of northern Poland, the majority of research sites are concentrated in this region. The Greater Poland Lake Districts

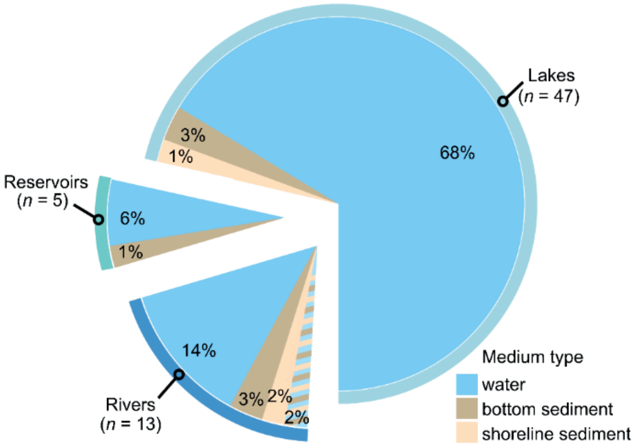

Fig. 3. Categorisation of water body types in microplastic studies in Polish surface waters based on studies published up to the end of 2024; source: own study

remain notably underexplored (Fig. 4). Notably, a comprehensive assessment of microplastic pollution levels has been conducted in 11 mountain lakes of the Tatra National Park, providing valuable insight into the current state of knowledge regarding lakes located in protected areas (Kiełtyk *et al.*, 2024). The most thoroughly studied lakes in terms of MPs pollution include Majcz Wielki and Kalwa, located in the Masurian Lake District (Kaliszewicz *et al.*, 2020; Pol *et al.*, 2023a), as well as the oxbow lake Dziekanowskie, situated in central Poland (Kaliszewicz *et al.*, 2020.; Karaban *et al.*, 2023) Several studies also examined different rivers, particularly major Polish watercourses such as the Vistula River, which was investigated at multiple locations mainly in big cities such as Cracow, Warsaw and Gdańsk (Zima, Wielgat and Cysewski, 2017; Połeć *et al.*, 2018; Kaliszewicz *et al.*, 2020; Sekudewicz, Dąbrowska and Syczewski, 2021; Dacewicz *et al.*, 2021; Dacewicz *et al*, 2022; Rytelewska and Dąbrowska, 2022; Nocoń, Moraczewska-Majkut and Wiśniowska, 2020; Dacewicz, Łobos-Moysa and Chmielowski, 2024). Water MPs in the Vistula River were analysed at 18 different locations, bottom sediments MPs at 3 locations, and shoreline sediments MPs at 1 location (Fig. 4, Tab. S1). Thus, the Vistula River can be considered the most thoroughly studied Polish aquatic ecosystem in terms of MPs pollution. The remaining rivers are scattered across Poland and were usually studied in urbanised areas (eg. Nocoń, Moraczewska-Majkut and Wiśniowska, 2018; Piskuła and Astel, 2022). Dam reservoirs have received relatively less attention but remain important sites for MPs accumulation, potentially posing a risk to the downstream river ecosystem during high-flow periods (Dhivert *et al.*, 2022). This distribution of research objects highlights a focus on standing waters while emphasising the need for further studies in dynamic riverine systems and dam reservoirs to fully assess the extent of MPs contamination in Polish inland waters.

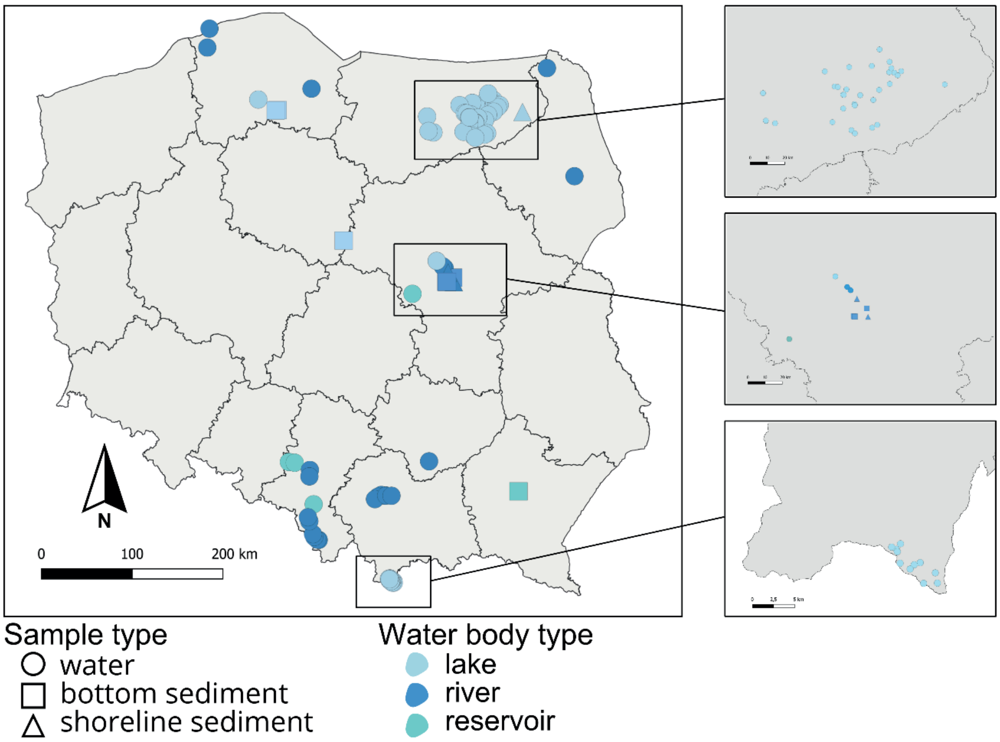

Fig. 4. Map of Poland illustrating the distribution of surface water and media types with analysed microplastics pollution; source: own study

METHODOLOGICAL DIFFERENCES IN SAMPLING AND ISOLATION OF MICROPLASTICS

Comparing the results of MP studies in aquatic environments can be challenging, mainly because researchers often apply a wide variety of methods for sampling and isolation of MPs (Dusaucy *et al.*, 2021; Thompson *et al.*, 2024). However, this may change in the near future, as standardised recommendations have already been developed for marine environments (GESAMP, 2019). It can be assumed that similar guidelines will be proposed for freshwater analyses. In the reviewed publications focused on MPs concentration in water, the vast majority of samples (68%) were collected using plankton nets with mesh sizes ranging from 20 µm to 250 µm (Tab. 1). The volume of water collected for MP analysis varied considerably, from just 1 dm^3 to as much as 100 dm^3. Occasionally, water was filtered directly through fine-pore filters with mesh sizes <5 µm (Połeć *et al.*, 2018) (Tab. 1).

To extract MPs from concentrated water samples, researchers most commonly used density separation with salt solutions such as NaCl (Dacewicz *et al.*, 2021; Dacewicz *et al.*, 2022; Sekudewicz, Dąbrowska and Syczewski, 2021; Fojutowski, 2024), $CaCl_2$, or $ZnCl_2$ (Zima, Wielgat and Cysewski, 2017), or alternatively with castor oil (Pol *et al.*, 2022; Pol *et al.*, 2023a; Pol *et al.*, 2023b) – Table 1. Organic matter was typically removed using either Fenton's reagent (Nocoń, Moraczewska-Majkut and Wiśniowska, 2020; Piskuła and Astel, 2022; Nocoń *et al.*, 2023) or 30% hydrogen peroxide (H_2O_2) (Kaliszewicz *et al.*, 2020; Dacewicz *et al.*, 2021, Dacewicz *et al.*, 2022). The isolated MPs were then collected using cellulose (C) or glass fibre filters (GF), such as GF/C or GF/F with pore size between 0.45 µm and 1.2 µm (Tab. 1). Sediment samples – taken from both bottom and shorelines zones – were collected using metal scoops, shovels from defined surface areas and depths (Rogowska *et al.*, 2021; Sekudewicz, Dąbrowska and Syczewski, 2021), or with specialised sediment corers and samplers that allowed for consistent sampling of layers, usually up to 5 cm thick (Krajewski, Hejduk and Hejduk, 2022; Fojutowski, 2024). Particles of MPs were isolated from these samples using salt solutions, mainly NaCl or $ZnCl_2$, followed by organic matter removal using sodium hypochlorite (NaClO) or 30% H_2O_2 (Rogowska *et al.*, 2021; Fojutowski, 2024) – Table 1. A critical challenge in extracting MPs from environmental samples is ensuring the accuracy and reliability of the results, particularly in distinguishing MPs from other sample components. This difficulty arises because MPs often resemble plant fibres, parts, plankton, or mineral particles, even under magnification, and these materials can remain in the sample despite prior chemical digestion or filtration (Reineccius, Bresien and Waniek, 2021; Strojny, Gruca-Rokosz and Cieśla, 2023). One of the methods used to distinguish MPs from other particles present in a sample is the hot needle test (also applied in the reviewed studies, e.g. Pol *et al.*, 2023a); however, it is characterised by low precision (Beckingham *et al.*, 2023).

The next step typically involved microscopic analysis of the isolated MPs, most commonly using a stereomicroscope and, less frequently, a conventional light microscope. The observations were accompanied by digital image analysis and photographic documentation (Dacewicz *et al.*, 2021, Dacewicz *et al.*, 2022). In most studies, the number of MPs, particle shape, size, and colour were identified (Tab. 1); however, the classification criteria for each of these attributes varied between studies. The final stage of MPs analysis involved determining the polymer type within a representative subset of particles (Tab. 1). Among studies on MPs in water, 27% included data on polymer identification (Połeć *et al.*, 2018; Kaliszewicz *et al.*, 2020; Sekudewicz, Dąbrowska and Syczewski, 2021; Piskuła and Astel, 2022; Nava *et al.*, 2023; Kiełtyk *et al.*, 2024). In the case of different sediment analyses, polymer types were determined in 50% of the studies (Sekudewicz, Dąbrowska and Syczewski, 2021; Rytelewska and Dąbrowska, 2022; Strojny, Gruca-Rokosz and Cieśla, 2023). Raman spectroscopy and FTIR spectroscopy were the most commonly used methods for this purpose (Tab. 1). Additionally, in a few individual studies, observations were conducted using scanning electron microscopy – SEM (Połeć *et al.*, 2018; Sekudewicz, Dąbrowska and Syczewski, 2021; Bhat and Janaszek, 2024).

MICROPLASTICS CONCENTRATION

The comprehensive analysis of MP water concentration across 55 freshwater ecosystems, including 43 lakes, 8 rivers, and 4 dam reservoirs (counted for 72 data cases) reveals a high level of variability in MP pollution (Tab. 2, Tab. S1). The mean concentration of MP in all types of water ecosystems was 6,599 MP·m^{-3}, whereas the median was significantly lower at 430 MP·m^{-3} (Tab. 2). The recorded concentrations ranged from 0.00 MP·m^{-3} (Rudawa River; Połeć *et al.*, 2018) to 245,000 MP·m^{-3} (Nida River; Bhat and Janaszek, 2024), highlighting substantial disparities among different aquatic environments. A very high coefficient of variation (*CV*) 475% confirms substantial variability in MP water contamination. These results underscore the heterogeneity of MP pollution across different freshwater ecosystems in Poland (Tab. 2). The variability in the concentrations of MP is likely to depend on different sampling methods (Tab. 1) e.g. the different limit for the smallest particle size, which has already been observed in other similar research comparisons (Gao *et al.*, 2024). An important factor contributing to the overestimation of MP concentrations in water may also be the incomplete verification of polymer particles and their misidentification as other materials, such as natural fibres. This is supported by an increasing number of reports emphasising the need to verify results using Raman or FTIR spectroscopy (Koelmans *et al.*, 2019). Therefore, the hot needle test may not be fully reliable as a solid identification method (Beckingham *et al.*, 2023).

Analysing the different types of water bodies, it becomes apparent that lakes have the most stable MP water pollution level. The mean concentration of MP (591 MP·m^{-3}) and median (430 MP·m^{-3}) are relatively close, indicating a more balanced MPs load. The *CV* (82%) suggest lower fluctuations compared to other surface water types (Tab. 2). These findings suggest that MPs pollution level in Polish lake waters is comparable to those observed in countries with a very high human development index (*HDI*). Chen *et al.* (2024) demonstrated in their study that areas with high *HDI* exhibited relatively low average MP water contamination (av. 548 MP·m^{-3}), compared to countries with low (17,791 MP·m^{-3}) and medium (18,947 MP·m^{-3}) development, where MP abundance was one to two orders of magnitude higher. The recorded minimum (0.2 MP·m^{-3}) and maximum (1,570 MP·m^{-3}) concentrations were observed in lakes Wdzydze in Bory Tucholskie (Nava *et al.*, 2023) and Miłkowskie at Masurian Lake District (Pol *et al.*, 2023a), respectively. This demonstrates a wide range of MPs pollution levels in Polish lakes

Table 1. Summary of key information on microplastics (MPs) research in Poland published up to the end of 2024

Reference	Investi-gation year	Water eco system type (number of objects)	Sample type	Number of samples	Sampling method (minimum pore size)	Isolation and purifi cation method	Quantitative and qualitative analysis of MP					Pollution source description
							concen-tration	shape	size	colour	polymer type (detection method)	
Zima, Wielgat and Cysewski (2017)	2016	river (1)	W	3	plankton net (200 μm)	$ZnCl_2$, H_2O_2, HCl	Y	NA	Y	NA	NA	H, MPF, P
Nocoń, Moraczewska-Majkut and Wiśniowska (2018)	ND	river (3)	W	ND	plankton net (250 μm)	Fenton reaction	Y	Y	NA	NA	NA	U, WWTP
Połeć *et al.* (2018)	2018	river (2)	W	ND	direct water sam-pling, 5 dm^3 filter GF5 (0.4 μm)	ND	ND	NA	NA	NA	Y (Raman)	ND
Kaliszewicz *et al.* (2020)	ND	lake, river (3)	W	9	plankton net (20 μm)	H_2O_2	ND	Y	Y	NA	Y (Raman)	AT, P, U
Nocoń, Moraczewska-Majkut and Wiśniowska (2020)	2018	dam reservoir (3)	W	9	plankton net (250 μm)	Fenton reaction	Y	Y	NA	NA	NA	AG, AT, H, WWTP
Dacewicz *et al.* (2021)	2021	river (1)	W	9	plankton net (250 μm)	NaCl, H_2O_2	Y	Y	Y	Y	NA	MPF, U
Rogowska *et al.* (2021)	2019	lake (1)	SS	37	200 g of sediments from 5 cm depth	NaCl, H_2O_2	Y	Y	NA	Y	NA	AG, P, SR, T, U
Sekudewicz, Dąbrowska and Syczewski (2021)	2018	river (1)	W / BS	6	plankton net (55 μm) / shovel	NaCl	Y	Y	Y	Y	Y (Raman, FTIR)	AT, H, P, PD, U
Dacewicz *et. al.* (2022)	2021	river (1)	W	18	plankton net (250 μm)	NaCl, H_2O_2	Y	Y	Y	Y	NA	MPF, U
Krajewski, Hejduk and Hejduk (2022)	ND	river (2)	BS	4	sediment corer with a 5 cm dia-meter and a sedi-ment depth 5 cm (14 μm)	$CaCl_2$, NaClO	Y	NA	NA	NA	NA	CA, P, PSP, U
Piskuła and Astel (2022)	2018	river (2)	W	42	plankton net (65 μm)	Fenton reaction	Y	Y	Y	Y	Y (ATR-FTIR)	TR, U, WWTP
Pol *et al.* (2022)	2019	river (2)	W	10	plankton net (40 μm)	castor oil	Y	Y	Y	Y	NA	P, PD, SR
Rytelewska, Dąbrowska (2022)	ND	river (2)	SS	2	surface layer × 1 m depth 5 cm	ND	Y	Y	Y	Y	Y (Raman)	U, WWTP

cont. Tab. 1

Reference	Investi-gation year	Water eco system type (number of objects)	Sample type	Number of samples	Sampling method (minimum pore size)	Isolation and purifi cation method	Quantitative and qualitative analysis of MP					Pollution source description
							concen-tration	shape	size	colour	polymer type (detection method)	
Karaban *et al.* (2023)	ND	lake, dam reservoir (2)	W	27	plankton net trauling (20, 200, 500 μm)	HNO_3, H_2O_2	Y	Y (only fibres)	Y	NA	NA	ND
Nava *et al.* (2023)	2022	lake (1)	W	ND	plankton net	ND	Y	NA	NA	NA	Y (Raman)	AN, MO, PD, U, WWTP
Nocoń *et al.* (2023)	ND	river (1)	W	6	plankton net (250 μm)	Fenton reaction	Y	NA	NA	Y	NA	AG, AN, H, T, WWTP
Pol *et al.* (2023a)	2019	lake (30)	W	30	plankton net (40 μm)	castor oil	Y	Y	Y	Y	NA	F, MO, T, WWTP, IS, H
Strojny, Gruca-Rokosz and Cieśla (2023)	ND	dam reservoir (1)	BS	3	ND	Fenton reaction	Y	Y	Y	NA	Y (LDIR)	H, T, U, AT
Bhat and Janaszek (2024)	2022	river (1)	W	5	direct water sampling	filtration directly on the filter	Y	Y	Y	Y	NA	F, H, T
Dacewicz, Łobos-Moysa and Chmielowski (2024)	2022	river (1)	W	6	plankton net (250 μm)	NaCl, H_2O_2	Y	Y	Y	Y	NA	MPF
Fojutowski (2024)	2021–2022	lake (3)	BS	45	gravity probe	NaCl, H_2O_2	Y	Y	Y	Y	NA	AG, AN, AT, IS, T
Kiełtyk *et al.* (2024)	2022	lake (12)	W	120	plankton net trauling (20 μm)	H_2O_2	Y	Y (only fibres)	Y	Y	Y (Raman)	AT, CA, MO, P, T

Explanations: ND = no data, sample type (W = water, BS = bottom sediment, SS = shoreline sediment), quantitative and qualitative analysis of MP (Y = yes, NA = not analysed, FTIR = Fourier transform infrared, ATR = Attenuated Total Reflectance, LDIR = laser direct infrared) regarding MP source description: AG = agriculture, AN = anthropopressure, AT = atmospheric transport, CA = catchment area, F = fishing, H = hydrological variables, IS = immediate surroundings of water ecosystem, MO = morphometric variables of water ecosystem, MPF = macroplastic fragmentation, P = precipitation, PD = population density, PSP = point source pollution, SR = surface runoff, T = tourism, TR – transportation, U = urbanisation, WWTP = waste water treatment plant.
Source: own study.

Table 2. Descriptive statistics for microplastics (MPs) concentrations[1)] in Polish freshwaters considering the type of water bodies

Statistic parameter	MP in water				MP in bottom sediment				MP in shoreline sediment			
	lakes	rivers	dam reser-voirs	all water ecosystem types	lakes	rivers	dam reser-voirs	all water ecosystem types	lakes	rivers	dam reser-voirs	all water ecosystem types
n	43	25	4	**72**	3	5	3	**11**	1	2	ND	NC
Average	591	17,860	805	**6,599**	11	3,169	65,833	**19,398**	27.45	11.5	ND	NC
Median	430	1,600	36	**430**	9	580	70,000	**580**	–	11.5	ND	NC
Minimum	0.2	0	23	**0**	4	190	7,500	**4**	–	11	ND	NC
Maximum	1,570	245,000	3,125	**245,000**	21	8,244	120,000	**120,000**	–	12	ND	NC
CV (%)	82	291	192	**475**	77	121	86	**202**	–	6	ND	NC

[1)] Measurement units of concentration depended on ecosystem type: water – MP·m^{-3}, bottom sediments – MP·kg^{-1} dry mass; shoreline sediments: lakes – MP·kg^{-1} wet mass, rivers – MP/sample.
Explanations: bold values = averages for all types of aquatic ecosystems (lakes, rivers and reservoirs), *n* = number of samples, *CV* = coefficient of variation, ND = no data, NC = not calculated.
Source: own study.

and confirms high variability of MP pollution in lake waters on both global and local scales (Dusaucy *et al.*, 2021; Cai *et al.*, 2022; Pan *et al.*, 2023). Therefore, studying MP contamination in all lakes that are crucial for the economy, tourism, or have strategic importance – such as those supplying water to the population – is of great significance. The disparities in the MPs concentration between Polish lakes can be linked to their characteristics (e.g. volume, surface, shoreline use, depth or tourism; Tab. 1), as it was confirmed in other review papers (Dusaucy *et al.*, 2021; Yang *et al.*, 2022; Li *et al.* 2023).

Rivers exhibit the highest variability and pollution level of MPs in Poland. The average MP concentration in rivers (17,860 MP·m^{-3}) is over 30 times higher than in lakes and 22 times higher than in reservoirs (Tab. 2). The *CV* (291%) confirms the high variability in MP river pollution level. The median value (1,600 MP·m^{-3}) is also high, indicating the presence of extreme outliers (i.e., heavily polluted rivers). The maximum concentration (245,000 MP·m^{-3}) noted in the Nida River (Bhat and Janaszek, 2024) suggests that this river is subject to extreme contamination, likely due to direct anthropogenic inputs. The Rudawa River was the only water body completely free of MP contamination (Połeć *et al.*, 2018). Although this may also be a result of the sampling methods used in this research or the sampling period. The lowest recorded MP pollution in river water was observed in the Vistula River in Tczew, with a concentration of 0.11 MP·m^{-3} (Zima, Wielgat and Cysewski, 2017). While it may appear that the Nida River shows the highest concentration of MP among Polish rivers, this does not necessarily mean that the region is the most polluted with synthetic polymers in Poland. The limited number of studies and lack of data from other medium-sized rivers may still provide an incomplete picture of the most polluted riverine environments. This is especially true for large countries, where hydrology and land use vary significantly (Lin *et al.*, 2024). This is the case in Poland as well. Dam reservoirs also show significant disparities in MPs pollution levels (Tab. 2). The mean concentration of MPs in water (805 MP·m^{-3}) is slightly higher than in lakes, but the median is very low (36 MP·m^{-3}), indicating that a limited number of reservoirs experience high MP pollution. The *CV* (192%) suggests moderate-to-high variability, implying that some reservoirs act as MPs sink while others remain relatively clean. The concentration range – from 23 MP·m^{-3} in Dzierżno Małe (Nocoń, Moraczewska-Majkut and Wiśniowska, 2020) to 3,125 MP·m^{-3} in Ruda Reservoir (Karaban *et al.*, 2023) – highlights substantial differences in pollution levels between individual dam reservoirs.

The concentration of MPs in bottom sediments of Polish surface waters exhibits a high degree of variability, but with a clear trend of increasing MP concentration – from lakes, through rivers, to dam reservoirs (Fig. 5). The mean concentra-

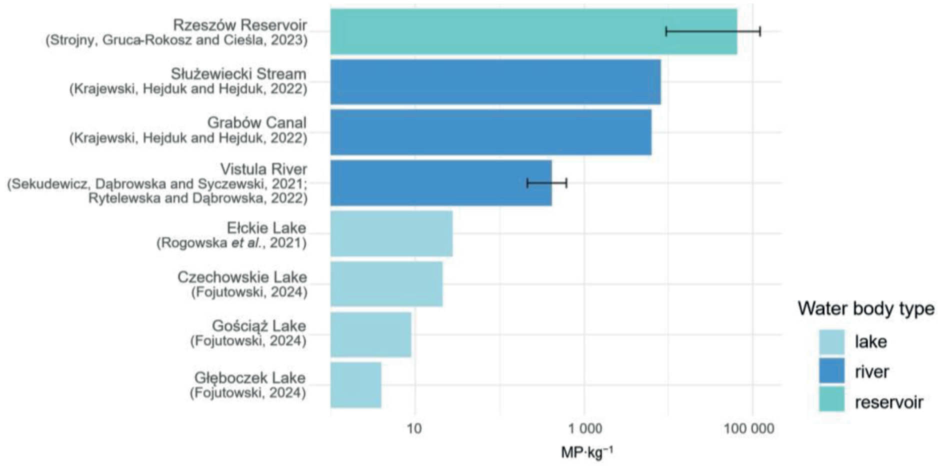

Fig. 5. Concentration of microplastic in bottom and shoreline sediment samples from different water body types; source: own study

tion of MPs in bottom sediments in all water ecosystem types was 19,398 MP·kg^{-1} d.m., whereas the median value is significantly lower at 580 MP·kg^{-1} d.m., indicating a strong right-skewed distribution. The *CV* with value 202% emphasises the significant dispersion within the dataset (Tab. 2). This is further evidenced by the wide range of values, from a minimum of 4 MP·kg^{-1} d.m. in Głęboczek Lake (Fojutowski, 2024) to a maximum of 120,000 MP·kg^{-1} d.m. in Rzeszów reservoir (Strojny, Gruca-Rokosz and Cieśla, 2023). Based on the descriptive statistics, the concentration of MPs in the bottom sediments of lakes demonstrates moderate variability. The mean concentration is 11 MP·kg^{-1} d.m. (Tab. 2). The range of MP concentration values in lakes spans from a minimum of 4 MP·kg^{-1} d.m. (Głęboczek Lake) to a maximum of 21 MP·kg^{-1} d.m. (Czechowskie Lake) (Fojutowski, 2024).

The concentration of MPs in river bottom sediments in Poland exhibits high variability and significantly elevated values compared to lake sediments. The mean concentration is 3,169 MP·kg^{-1} d.m., while the median is substantially lower at 580 MP·kg^{-1}, indicating a strong right-skewed distribution (Tab. 2). In the case of river sediments *CV* is lower than in case of lakes which confirms the lower variability of this parameter in flowing water ecosystems (Tab. 2). The range of MP concentrations in river sediments is broad, spanning from a minimum of 190 MP·kg^{-1} d.m. in the Vistula River in Warsaw (Sekudewicz, Dąbrowska and Syczewski, 2021) to a maximum of 8,244 MP·kg^{-1} d.m. in Potok Służewiecki also in Warsaw (Krajewski, Hejduk and Hejduk, 2022). Contamination of bottom sediments with MPs was investigated only in three dam reservoirs. The mean MP concentration in bottom sediments of dam reservoirs was the highest among the examined aquatic ecosystem types, amounting to 65,833 MP·m^{-3}, with a relatively low *CV* value 86% (Tab. 2).

Contamination of shoreline sediments with MPs is poorly characterised, with available data limited to just one lake – Ełckie (Rogowska *et al.*, 2021) and two rivers – Vistula and Wilanówka (Rytelewska and Dąbrowska, 2022). The different units used by the authors of these studies make it impossible to compile the data comprehensively (Tab. 2). The noted concentration of MP in shoreline sediments of Ełckie Lake was 27.45 MP·kg^{-1} wet mass. The mean concentration of MP in shoreline sediments in rivers was 11.5 MP per sample, and the *CV* was 6% (Tab. 2). In the study conducted in the German rivers, i.e. Main and Rhine (Klein, Worch and Knepper, 2015), very high concentrations were recorded (228–3,763 MP·kg^{-1}), which shows that this is a seriously threatened environment due to MP pollution. The values were correlated with population density. In the Polish study by Rytelewska and Dąbrowska (2022), samples collected in the capital city of Poland, where the population density substantially exceeded even the highest values reported by Klein, Worch and Knepper (2015) concentrations of MP are relatively low (11–12 MP per sample).

MICROPLASTICS SHAPE

One of the most frequently identified characteristics of MPs in studies conducted in aquatic ecosystems in Poland is their shape. This parameter was analysed in nearly 80% of the reviewed studies (Tab. 1). Analysis of MP in surface waters of Poland reveals a diversity of shapes across different media: water, bottom sediment, and shoreline sediment. The number of identified shapes typically ranges from 3 to 6 (Fig. 6). In water samples, fragments (20–74.5%), fibres (0.5–44%), and beads (0–25%) were the most commonly observed shapes, with smaller proportions of foams and films. Yang *et al.* (2022) have noted similar proportions for European freshwaters, but on other continents, fibres and films were dominating forms (Cai *et al.*, 2022; Chen D. *et al.*, 2024). Bottom sediment samples primarily contain fragments (85%) and fibres (15%) (Fig. 6; Fojutowski, 2024). The number of identified shapes in shoreline sediments ranges from 3 to 4 (Fig. 6). Shoreline sediment samples were dominated by fibres (9–64%) and fragments (9.0–47.6%), with the addition of other forms (Rogowska *et al.*, 2021; Rytelewska and Dąbrowska, 2022). These findings highlight the variability in MP shape distribution depending on the medium and methodology used in the analysis. The morphological characteristics of MPs are related to their origin and source. Fibres come from different types of textiles, fishing equipment, fragments from the

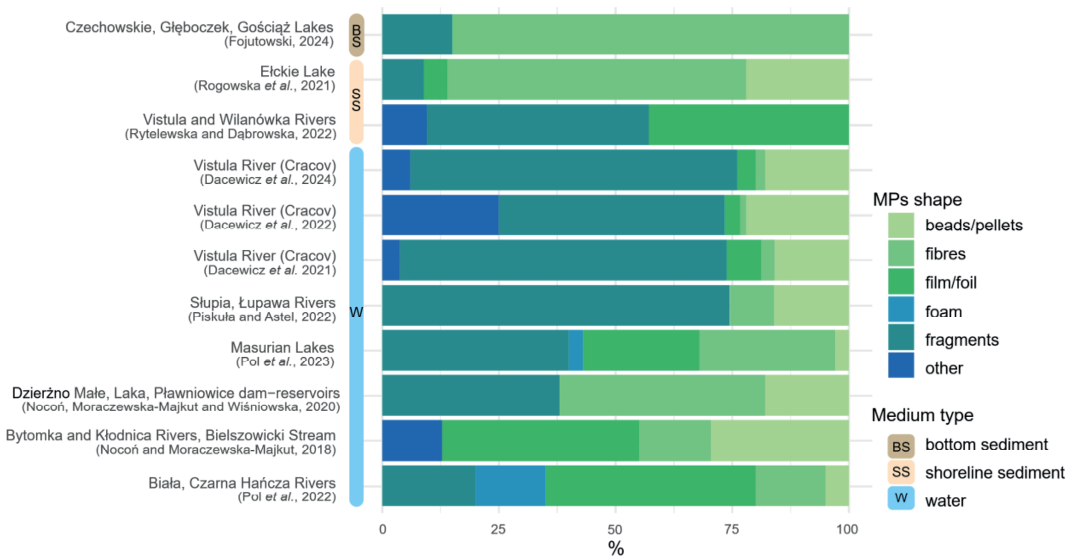

Fig. 6. Microplastics (MPs) shapes distribution in different Polish MPs studies concerning media types; source: own study

degradation of MPs, and films originating from packaging materials and agriculture (Sighicelli *et al.*, 2018; Meng, Kelly, and Wright, 2020; Yang *et al.*, 2022). In some cases, elevated concentrations of MPs in waters with a fibre shape were linked to the presence of wastewater treatment plants (WWTPs) within the area influencing a given aquatic ecosystem (Pol *et al.*, 2022; Pol *et al.*, 2023a).

MICROPLASTICS SIZE

In many studies, particle size was considered a key parameter for characterising MPs. Among the 22 analysed studies, 15 have mentioned MPs size in some way (Tab. 1). Some studies report MPs size results for individual samples (Strojny, Gruca-Rokosz and Cieśla, 2023), others for specific lakes or rivers (Kaliszewicz *et al.*, 2020; Pol *et al.*, 2022; respectively), and some for the entire study (Pol *et al.*, 2023a; Fojutowski, 2024). The most commonly used method for measuring MP sizes involves software integrated with a camera attached to a microscope, significantly facilitating counting and data recording. The reported size ranges of the examined MPs vary, particularly at the lower limits (Fig. 7). The lower detection limit is often determined by the mesh/filter pore size, whereas the upper limit is conventionally set at 5 mm, in accordance with the definition of MP (GESAMP, 2019; Thompson *et al.*, 2024). However, some studies also included mesoplastics – particles >5 mm (Fig. 7) (Zima, Wielgat and Cysewski, 2017; Dacewicz *et al.*, 2021, Dacewicz *et al.*, 2022; Karaban *et al.*, 2023; Kiełtyk *et al.*, 2024). Certain studies provide digitally measured size distributions (Pol *et al.*, 2022; Pol *et al.*, 2023a; Pol *et al.*, 2023b), while others focus on individual particles (Bhat and Janaszek, 2024). To enhance result interpretation, MP particles are frequently categorised into size classes. The classification approach varies across studies – some divide particles into 1 mm increments (Pol *et al.*, 2022; Pol *et al.*, 2023a; Fojutowski, 2024), while others employ broader categories, such as <1 mm, 1–5 mm, and >5 mm (Kaliszewicz *et al.*, 2020) or <1 mm, 1–2 mm, 2–5 mm (GESAMP, 2019). The most frequently observed size class comprises particles smaller than 1 mm. One study considered only visually detectable particles (Nocoń, Moraczewska-Majkut and Wiśniowska, 2020), while two others focused exclusively on fibrous MPs (Karaban *et al.*, 2023; Kiełtyk *et al.*, 2024). Two studies also considered the surface area of the particles (Piskuła and Astel, 2022; Strojny, Gruca-Rokosz and Cieśla, 2023; Dacewicz, Łobos-Moysa and Chmielowski, 2024). The lack of standardisation in the classification of MP size groups considerably limits the comparability of findings across studies.

MICROPLASTICS COLOUR

The colour of MP particles was considered in 13 out of 22 studies (Tab. 1). The number of distinguished colours varied across studies, ranging from 3 to 9, while a total of 11 different colours were reported across all studies: red, blue, black, transparent, green, white, yellow, grey, pink, purple, and silver (Fig. 8). Many studies also included an "other" category in their colour classification. Most studies reported either the percentage composition of each colour or the absolute number of particles for each colour category. In one study, only the presence of certain colours was noted, without specifying quantities (Bhat and Janaszek, 2024). Red, blue, and black were the only colours present in all studies, with their proportions ranging from 4–31%, 2–67%, and 4–65% respectively. In addition to these dominant colours, white (up to 28%) was evident in shoreline sediments in the Wisła River and the Wilanówka River (Rytelewska and Dąbrowska, 2022). Transparent polymers were also frequently observed (up to 35%) in the water samples of Biała River and Czarna Hańcza River (Pol *et al.*, 2022) (Fig. 8). Silver was reported only in one study of shoreline sediment of Ełckie Lake (Rogowska *et al.*, 2021), where it accounted for 26%,

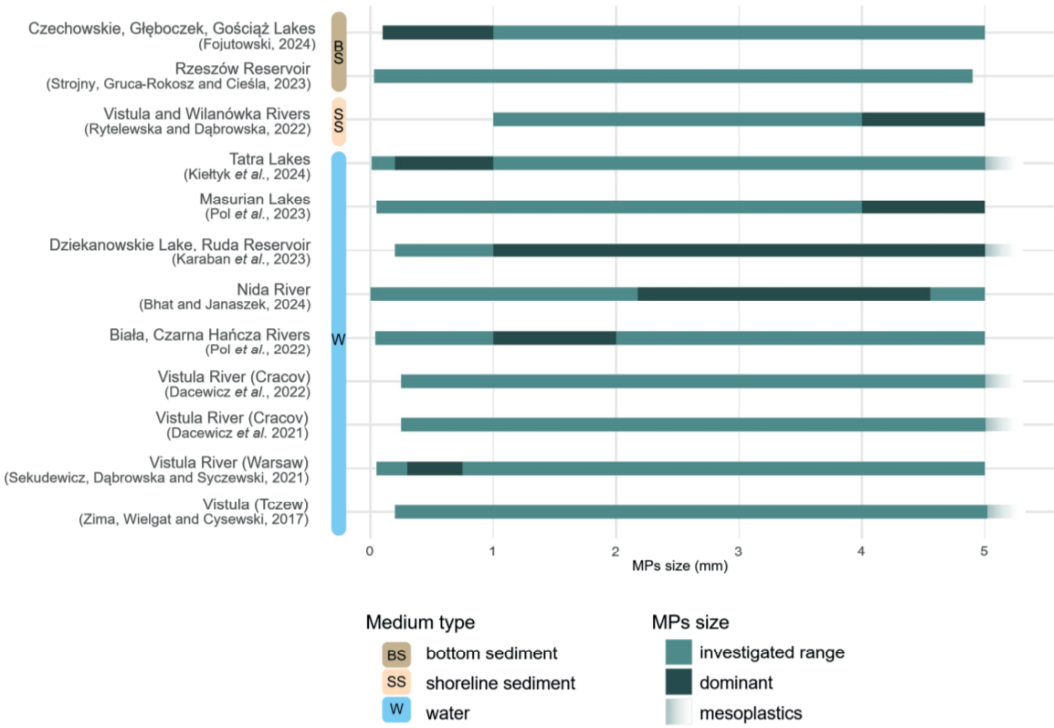

Fig. 7. Microplastics (MPs) size range and mesoplastic analysis mentioned in reviewed studies; source: own study

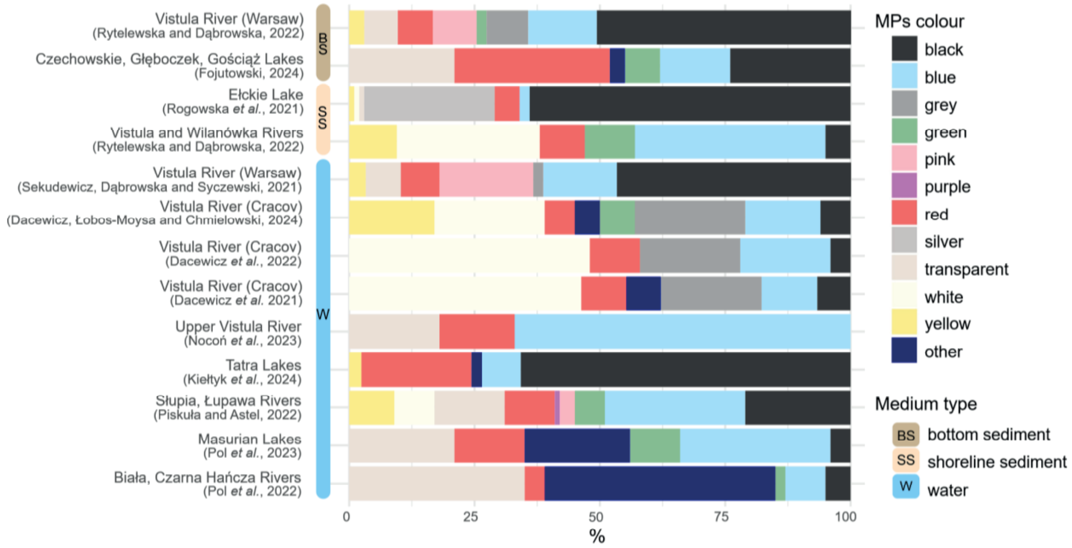

Fig. 8. Microplastics (MPs) colours distribution in Polish freshwaters based on reviewed studies; source: own study

and purple appeared exclusively in the study on the Słupia River and the Łupawa River (Piskuła and Astel, 2022). Yellow was the most abundant in the Wisła River in Dacewicz, Łobos-Moysa and Chmielowski (2024) research, accounting 22% (from 14.5% between 3D (dimensions) MPs to 40.3% 2D and 1D MPs). However, this may indicate the progressive ageing of the polystyrene granules under UV light and their gradual degradation which leads to gradual yellowing (Dacewicz, Łobos-Moysa and Chmielowski, 2024). In global meta-analyses of MPs in lakes, the dominant colours were transparent and blue, accounting for 34 and 21% respectively in surface waters, and 27.5 and 17.9% respectively in sediments (Chen D. *et al.*, 2024). This is likely due to the still limited dataset, particularly for sediments, and possibly also influenced by the climatic conditions in Poland. The global overrepresentation of transparent MPs is attributed to the discoloration process (Asim *et al.*, 2024), which occurs more easily and rapidly in warmer climate zones with higher UV index. Many disposable products are made of transparent or simply coloured plastics, and external factors or the digestion protocols used during laboratory analysis tend to bleach their colours (Jiang *et al.*, 2019). The high proportion of black-coloured particles in some studies on MPs in water (Sekudewicz, Dąbrowska and Syczewski, 2021; Kiełtyk *et al.*, 2024) and bottom or shoreline sediments (Rogowska *et al.*, 2021; Sekudewicz, Dąbrowska and Syczewski, 2021) – Figure 7 – is rather surprising. Their presence may be linked to nearby road traffic and the migration of tire wear particles – TWP (Mierzyńska *et al.*, 2024), as well as tourist activity – such as the abrasion of shoe soles and fibres from commonly black trekking clothing (Kiełtyk *et al.*, 2024). Another possible reason is heavy contamination of MPs, which over time may cause them to darken through secondary processes (Asim *et al.*, 2024).

MICOPLASTICS POLYMERS IDENTIFICATION

Among all the reviewed studies, a minority (36%) included qualitative analyses of MP polymer type (Tab. 1). Raman spectroscopy was the most commonly used method (Połeć *et al.*, 2018; Kaliszewicz *et al.*, 2020; Sekudewicz, Dąbrowska and Syczewski, 2021; Rytelewska and Dąbrowska, 2022; Nava *et al.*, 2023; Kiełtyk *et al.*, 2024), while Fourier transform infrared (FTIR) spectroscopy and laser direct infrared (LDIR) were applied in only three cases (Sekudewicz, Dąbrowska and Syczewski, 2021; Piskuła and Astel, 2022; Strojny, Gruca-Rokosz and Cieśla, 2023). Polymer identification analyses in MP samples from water were performed in 37% of the studies. Raman spectroscopy was applied in five of these studies, while FTIR was used in two (Tab. 1). For bottom sediments and shoreline sediments MP analyses for polymer identification were carried out in three studies using Raman spectroscopy, FTIR, and the LDIR method (Tab. 1). Based on the collected data, the most frequently identified polymers in MPs were polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polyurethane (PU) (Kaliszewicz *et al.*, 2020; Sekudewicz, Dąbrowska and Syczewski, 2021; Piskuła and Astel, 2022; Kiełtyk *et al.*, 2024). In one study, Raman spectroscopy was used to detect MPs without specifying the polymer types (Połeć *et al.*, 2018). In bottom and shoreline sediment samples, the most commonly reported polymers were PE, PP, and PA (Sekudewicz, Dąbrowska and Syczewski, 2021; Strojny, Gruca-Rokosz and Cieśla, 2023). An analysis of lake environments around the world shows that PE, PP, and PET are the most abundant polymer types in their surface water and bottom sediments (Chen D. *et al.*, 2024). In China, in addition to the materials mentioned, PVC also plays a significant role (Cai *et al.*, 2022).

MICROPLASTICS SUPPORTING ANALYSIS

In several studies, beyond the most frequently reported parameters directly associated with MPs pollution in aquatic environments, additional supporting analyses have been conducted. These supplementary investigations enhance the overall findings and provide a more comprehensive understanding of the issue. Among them were water chemistry assessments, including evaluations of water quality (Bhat and Janaszek, 2024). Some studies also incorporated hydrological, meteorological, and catchment data (Pol *et al.*, 2022; Nava *et al.*, 2023; Kiełtyk *et al.*, 2024), which is particularly valuable given the growing recognition that hydrological characteristics are among the key factors influencing both the quantity and quality of MPs contamination in surface waters (Calvahlo de *et al.*, 2021). A particularly interesting line of inquiry involves the search for universal factors that promote the migration of MPs from catchment areas. Pol *et al.* (2023a) described a significant positive correlation between anthropogenic shoreline modification and MP pollution level in lake waters. This parameter was defined as the shoreline urbanisation index (*SUI*). Another noteworthy aspect involves the analysis of heavy metals, which appears to be a valuable approach, particularly in light of emerging evidence suggesting that harmful substances can be transported along the water environment on the surface of MPs. This includes heavy metals, toxic compounds, and even pathogenic microorganisms (Pol *et al.*, 2023b; Arif *et al.*, 2024; Bhat and Janaszek, 2024). Some studies have also provided detailed characterisations of MPs particles, employing methods such as SEM (Połeć *et al.*, 2018; Sekudewicz, Dąbrowska and Syczewski, 2021; Bhat and Janaszek, 2024). An interesting approach is the multidimensional analysis of MPs (digital image processing), which enables to determine 2D and 3D shape descriptors of polymer particles (Dacewicz, Łobos-Moysa and Chmielowski, 2024). In research focused on bottom sediment contamination, factors such as sediment age were taken into account and related to the degree of contamination in different layers (Fojutowski, 2024).

SOURCES OF MICROPLASTICS

Almost all of the reviewed publications attempt to identify potential threats to aquatic environments and the sources of MPs (Tab. 1). Most commonly, the elevated levels of MPs pollution in surface waters in Poland are attributed to the degree of catchment urbanisation and population density (Tab. 1). In urbanised areas, WWTPs are identified as having a significant impact on freshwater ecosystems MPs contamination (Cai *et al.*, 2022; Pol *et al.*, 2022; Pol *et al.*, 2023a). However, it is important to note that these facilities also play a crucial role in reducing the concentration of MPs in raw sewage by up to 90% on average (Talvitie *et al.*, 2017). It is also crucial to introduce another stage of municipal sewage treatment, which will limit the release of MP along with the treated sewage (Dacewicz, Łobos-Moysa and Chmielowski, 2024). On the other hand, some MPs may be transported to the water environments with sludge (Meng, Kelly and Wright, 2020). In the case of Polish lakes, particular attention is paid to tourism (Pol *et al.*, 2023a) and recreational activities (Kiełtyk *et al.*, 2024), which are considered an increasing source of MPs, also in other parts of the world, particularly those that are popular tourist destinations (Cai *et al.*, 2022; Han *et al.*, 2024). Another important factor influencing the presence of MPs in both the water column and bottom and shoreline sediments is hydrological condition (Nocoń, Moraczewska-Majkut, Wiśniowska, 2023; Bhat and Janaszek, 2024) (Tab. 1), which, according to researchers, is often underestimated despite its regulatory role in MP migration from catchments – along with precipitation levels (Yang *et al.*, 2022; Chen D. *et at.*, 2024). Surface runoff (Rogowska *et al.*, 2021; Pol *et al.*, 2022), closely linked to agricultural activity, is also identified as a contributing factor (Grbić *et al.*, 2020; Cai *et al.*, 2022). In many studies, the role of atmospheric transport is emphasised (Kaliszewicz *et al.*, 2020; Sekudewicz, Dąbrowska and Syczewski, 2021; Fojutowski, 2024; Kiełtyk *et al.*, 2024). Less attention has been given to catchment size, morphometric variables of aquatic ecosystems, fishing activity (Krajewski, Hejduk and Hejduk, 2022; Pol *et al.*, 2023; Strojny, Gruca-Rokosz and Cieśla, 2023; Kiełtyk *et al.*, 2024) – Table 1.

RESEARCH GAPS AND FUTURE PERSPECTIVES

The available body of literature confirms that MPs contamination of surface waters in Poland is a widespread issue, regardless of the region. The presence of MPs in water and sediments poses a significant threat to aquatic organisms (Piskuła and Astel, 2022; Fontes *et al.*, 2024) and, through trophic transfer (Bhatt and Chauhan, 2023), potentially to humans (Cox *et al.*, 2019; Arif *et al.*, 2024). Key drivers of MPs pollution include anthropopression, urbanisation, transportation, WWTPs, agriculture, and even tourism and recreational activities. Although the number of MP studies conducted in Polish surface waters is not negligible, the scope and comprehensiveness of research covering the country's major aquatic ecosystems remain limited. The selection of study sites has largely been influenced by the location of academic institutions, resulting in fragmented data. As a consequence, our understanding of MP contamination in Poland's largest and most ecologically valuable lakes is still minimal or entirely lacking. The same holds true for the country's main rivers. The picture emerging from the existing studies is incomplete, and while many findings are valuable, methodological inconsistencies often hinder direct comparison.

A thorough understanding of the problem is essential for planning an effective mitigation strategy. One approach would be to incorporate MPs analysis into the framework of Poland's State Environmental Monitoring program. For comparison, countries such as Germany and the Netherlands have already implemented long-term monitoring of MPs in surface waters and river sediments as part of their national water quality assessment programs. In Norway, MPs have been officially integrated into national strategies addressing chemical pollution and marine litter (Alling *et al.*, 2024). Integrating Poland into similar initiatives would represent an important step toward a coherent and harmonised water protection policy aligned with the objectives of the EU Water Framework Directive.

A critical step toward improving the assessment of MPs contamination in Polish freshwater ecosystems is the global problem, mentioned by numerous researchers, the standardisation of methodologies (e.g., GESAMP, 2019; Hartmann *et al.*, 2019). This applies to all stages of investigation, starting from sample collection (water and sediment), through MPs extraction and purification, to their identification and quantification. Equally important is the harmonisation of data reporting formats. Standard descriptions for particle shape, size, colour, and polymer type should be consistently applied across different studies. Although many of these characteristics are commonly reported, inconsistencies in classification systems and measurement protocols still occur, obscuring the overall picture and limiting the comparability of results across different regions and studies. Furthermore, there is a growing recognition of the need to include advanced analytical techniques such as FTIR or Raman spectroscopy, which enable more precise polymer identification. The adoption of uniform quality assurance and quality control (QA/QC) protocols, along with inter-laboratory calibration exercises, could significantly enhance data reliability. In the context of policymaking and environmental risk assessment, standardised approaches would not only improve scientific understanding but also support more effective environmental management strategies at national and European levels.

CONCLUSIONS

This review provides the first comprehensive synthesis of available data on microplastic (MP) contamination in Polish freshwater ecosystems. The analysis of 22 studies published up to the end of 2024 reveals significant gaps in current MPs research. Despite the increasing number of studies from 2017 (the first publication on MP in Polish freshwaters), the focus remains heavily biased toward water samples (73%), with sediments (14%) and shoreline sediments (9%) being considerably underrepresented. Notably, only 4% of the studies examined both water and bottom sediments together. Water contamination with MPs has been confirmed in lakes, rivers and dam reservoirs, with the highest average concentration in rivers (17,860 MP·m^{-3}). In studies on MP contamination of bottom sediments in freshwater bodies in Poland, the highest concentrations were recorded in dam reservoirs (av. 65,833 MP·kg^{-1} d.m.), followed by rivers (av. 3,169 MP·kg^{-1} d.m.), with the lowest values observed in lakes (av. 11 MP·kg^{-1} d.m.). The results demonstrate high variability in MP concentrations and highlight the strong influence of catchment characteristics, urbanisation, tourism, and wastewater treatment infrastructure. The lack of standardised methodologies for sampling, extraction, and particle classification presents a major obstacle to cross-study comparisons. Moreover, the limited number of studies with polymer identification significantly constrains our understanding of the sources of MPs and their potential risk. The current state of knowledge reveals a significant spatial imbalance in research on MPs in Polish surface waters – some regions have been thoroughly studied, while others remain virtually unexplored. These findings highlight the urgent need for more comprehensive and spatially representative investigations. Incorporating MP monitoring into national environmental programs would support evidence-based policy-making and contribute to European Union-wide efforts to protect aquatic ecosystems from plastic pollution.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_67_Zielinski.pdf.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interests.

ACKNOWLEDGEMENTS

The authors express their gratitude to Mariusz Wojtalewski and Benedykt Ambrożko for their support in collecting data and map preparation.

REFERENCES

Allen, S. *et al.* (2019) "Atmospheric transport and deposition of microplastics in a remote mountain catchment," *Nature Geoscience*, 12(5), pp. 339–344. Available at: https://doi.org/10.1038/s41561-019-0335-5.

Alling, V.K.G. *et al.* (2024) *Monitoring of microplastics in the Norwegian environment (MIKRONOR) 2023.* Oslo: Norwegian Institute for Water Research. Available at: https://munin.uit.no/bitstream/handle/10037/ (Accessed: May 19, 2025).

Arif, Y. *et al.* (2024) "Microplastics and nanoplastics: source, behavior, remediation, and multi-level environmental impact," *Journal of Environmental Management*, 356, 120618. Available at: https://doi.org/10.1016/j.jenvman.2024.120618.

Arthur, C., Baker, J.E. and Bamford, H. A. (2009) *Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris*. Tacoma, WA, USA, September 9–11, 2008. Silver Spring, MA: NOAA Available at: https://repository.library.noaa.gov/view/noaa/2509 (Accessed: May 22, 2025).

Asim, N. *et al.* (2024) "Colours and microplastics: Bridging the gap between art, science and sustainability," *Sustainable Materials and Technologies*, 43, e01152. Available at: https://doi.org/10.1016/j.susmat.2024.e01152.

Beckingham, B. *et al.* (2023) "Hot or not: Systematic review and laboratory evaluation of the hot needle test for microplastic identification," *Microplastics and Nanoplastics*, 3(1), 8. Available at: https://doi.org/10.1186/s43591-023-00056-4.

Bergmann, M. *et al.* (2019) "White and wonderful? Microplastics prevail in snow from the Alps to the Arctic," *Science Advances*, 5(8), eaax1157. Available at: https://doi.org/10.1126/sciadv.aax1157.

Bhat, M.A. and Janaszek, A. (2024) "Delving into river health: unveiling microplastic intrusion and heavy metal contamination in freshwater," *Discover Environment*, 2(1), 61. Available at: https://doi.org/10.1007/s44274-024-00101-w.

Bhatt, V. and Chauhan, J.S. (2023) "Microplastic in freshwater ecosystem: Bioaccumulation, trophic transfer, and biomagnification," *Environmental Science and Pollution Research*, 30(4), pp. 9389–9400. Available at: https://doi.org/10.1007/s11356-022-24529-w.

Buchanan, J.B. (1971) "Pollution by synthetic fibres," *Marine Pollution Bulletin*, 2(2), pp. 23–23. Available at: https://doi.org/10.1016/0025-326X(71)90136-6.

Büks, F. and Kaupenjohann, M. (2020) "Global concentrations of microplastics in soils – A review," *SOIL*, 6, pp. 649–662. Available at: https://doi.org/10.5194/soil-6-649-2020.

Cai, X. *et al.* (2022) "Analysis on advances and characteristics of microplastic pollution in China's lake ecosystems," *Ecotoxicology and Environmental Safety*, 232, 113254. Available at: https://doi.org/10.1016/j.ecoenv.2022.113254.

Carpenter, E.J. and Smith Jr, K.L. (1972) "Plastics on the Sargasso Sea surface," *Science*, 175(4027), pp. 1240–1241. Available at: https://doi.org/10.1126/science.175.4027.1240.

Carvalho de, A.R. *et al.* (2021) "Urbanisation and hydrological conditions drive the spatial and temporal variability of microplastic pollution in the Garonne River," *Science of The Total Environment*, 769, 144479. Available at: https://doi.org/10.1016/j.scitotenv.2020.144479.

Castro, R.O., Silva da, M.L. and Araújo de, F.V. (2018) "Review on microplastic studies in Brazilian aquatic ecosystems," *Ocean & Coastal Management*, 165, pp. 385–400. Available at: https://doi.org/10.1016/j.ocecoaman.2018.09.013.

Chalmin, P. (2019) "The history of plastics: from the Capitol to the Tarpeian Rock. Field actions science reports," *The Journal of Field Actions*, Spec. Iss. 19, pp. 6–11. Available at: https://journals.openedition.org/factsreports/5071 (Accessed: May 23, 2025).

Chen, D. *et al.* (2024) "Global patterns of lake microplastic pollution: Insights from regional human development levels," *Science of The Total Environment*, 954, 176620. Available at: https://doi.org/10.1016/j.scitotenv.2024.176620.

Chen, H. *et al.* (2024) "Hotspots lurking underwater: Insights into the contamination characteristics, environmental fates and impacts on biogeochemical cycling of microplastics in freshwater sediments," *Journal of Hazardous Materials*, 476, 135132. Available at: https://doi.org/10.1016/j.jhazmat.2024.135132.

Cole, M. *et al.* (2013) "Microplastic ingestion by zooplankton," *Environmental Science & Technology*, 47(12), pp. 6646–6655. Available at: https://doi.org/10.1021/es400663f.

Colton Jr, J.B., Burns, B.R. and Knapp, F.D. (1974) "Plastic particles in surface waters of the Northwestern Atlantic: The abundance, distribution, source, and significance of various types of plastics are discussed," *Science*, 185(4150), pp. 491–497. Available at: https://doi.org/10.1126/science.185.4150.491.

Cox, K.D. *et al.* (2019) "Human consumption of microplastics," *Environmental Science & Technology*, 53(12), pp. 7068–7074. Available at: https://doi.org/10.1021/acs.est.9b01517.

Dacewicz, E. *et al.* (2021) "Mikroplastik i mezoplastik w zastoiskach wód Wisły na obszarach silnie zurbanizowanych powiatu krakowskiego – badania wstępne [Microplastics and mesoplastics in Vistula River backwaters within highly urbanised areas of the Kraków district – Preliminary study]," *Acta Scientiarum Polonorum. Formatio Circumiectus*, 20(3–4), pp. 5–17. Available at: http://doi.org/10.15576/ASP.FC/2021.20.3/4.5.

Dacewicz, E. *et al.* (2022) "Mikroplastik i mezoplastik w wybranych wodach płynących na obszarze aglomeracji krakowskiej [Microplastics and mesoplastics in selected flowing waters within the Kraków metropolitan area]," *Instal*, 9/2022, pp. 43–47. Available at: https://doi.org/10.36119/15.2022.9.5.

Dacewicz, E., Łobos-Moysa, E. and Chmielowski, K. (2024) "Identification tools of microplastics from surface water integrating digital image processing and statistical techniques," *Materials*, 17(15), 3701. Available at: https://doi.org/10.3390/ma17153701.

Dhivert, E. *et al.* (2022) "Microplastic trapping in dam reservoirs driven by complex hydrosedimentary processes (Villerest Reservoir, Loire River, France)," *Water Research*, 225, 119187. Available at: https://doi.org/10.1016/j.watres.2022.119187.

Dokl, M. *et al.* (2024) "Global projections of plastic use, end-of-life fate and potential changes in consumption, reduction, recycling and replacement with bioplastics to 2050," *Sustainable Production and Consumption*, 51, pp. 498–518. Available at: https://doi.org/10.1016/j.spc.2024.09.025.

Dris, R. *et al.* (2015) "Microplastic contamination in an urban area: A case study in Greater Paris," *Environmental Chemistry*, 12(5), pp. 592–599. Available at: https://doi.org/10.1071/EN14167.

Dris, R. *et al.* (2016) "Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?," *Marine Pollution Bulletin*, 104(1–2), pp. 290–293. Available at: https://doi.org/10.1016/j.marpolbul.2016.01.006.

Dusaucy, J. *et al.* (2021) "Microplastic pollution of worldwide lakes," *Environmental Pollution*, 284, 117075. Available at: https://doi.org/10.1016/j.envpol.2021.117075.

EC (2024) "Commission Delegated Decision (EU) 2024/1441 of 11 March 2024 supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by laying down a methodology to measure microplastics in water intended for human consumption (notified under document C(2024) 1459)," *OJ L*, 2024/1441. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024D1441 (Accessed: July 28, 2025).

Eriksen, M. *et al.* (2013) "Microplastic pollution in the surface waters of the Laurentian Great Lakes," *Marine Pollution Bulletin*, 77(1–2), pp. 177–182. Available at: https://doi.org/10.1016/j.marpolbul.2013.10.007.

Eriksen, M. *et al.* (2023) "A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans – Urgent solutions required," *PLOS ONE*, 18(3), e0281596. Available at: https://doi.org/10.1371/journal.pone.0281596.

Fojutowski, M. (2024) "Lake sediments as microplastic sink: The case of three lakes from Northern and Central Poland," *Quaestiones Geographicae*, 43(3), pp. 103–112. Available at: https://doi.org/10.14746/quageo-2024-0029.

Fontes, B.L.M. *et al.* (2024) "The possible impacts of nano and microplastics on human health: Lessons from experimental models across multiple organs," *Journal of Toxicology and Environmental Health*, P. B, 27(4), pp. 153–187. Available at: https://doi.org/10.1080/10937404.2024.2330962.

Gao, S. *et al.* (2024) "A review on microplastics in major European rivers," *Wiley Interdisciplinary Reviews: Water*, 11(3), e1713. Available at: https://doi.org/10.1002/wat2.1713.

GESAMP (2019) "Guidelines for the monitoring and assessment of plastic litter in the ocean," *Reports and Studies*, 99. Available at: https://wedocs.unep.org/handle/20.500.11822/30009 (Accessed: May 23, 2025).

Gong, H. *et al.* (2023) "Microplastic pollution in water environment of typical nature reserves and scenery districts in southern China," *Science of the Total Environment*, 903, 166628. Available at: https://doi.org/10.1016/j.scitotenv.2023.166628.

Grbić, J. *et al.* (2020) "Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources," *Water Research*, 174, 115623. Available at: https://doi.org/10.1016/j.watres.2020.115623.

Han, X. *et al.* (2024) "Heterogenization of microplastic communities in lakes of the Qinghai-Tibetan Plateau driven by tourism and transport activities," *Journal of Hazardous Materials*, 477, 135255. Available at: https://doi.org/10.1016/j.jhazmat.2024.135255.

Hartmann, N.B. *et al.* (2019) "Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris," *Environmental Science & Technology*, 53(3), pp. 1039–1047. Available at: https://doi.org/10.1021/acs.est.8b05297.

Horton, A.A. *et al.* (2017) "Large microplastic particles in sediments of tributaries of the River Thames, UK – Abundance, sources and methods for effective quantification," *Marine Pollution Bulletin*, 114(1), pp. 218–226. Available at: https://doi.org/10.1016/j.marpolbul.2016.09.004.

Islam, F. and Khan, R.A. (2024) "A review of plastic threat to environment," *International Journal of Environment and Climate Change*, 14(11), pp. 872–887. Available at: https://doi.org/10.9734/ijecc/2024/v14i114594.

Jiang, C. *et al.* (2019) "Microplastic pollution in the rivers of the Tibet Plateau," *Environmental Pollution*, 249, pp. 91–98. Available at: https://doi.org/10.1016/j.envpol.2019.03.022.

Kaliszewicz, A. *et al.* (2020) "The contamination of inland waters by microplastic fibres under different anthropogenic pressure: Preliminary study in Central Europe (Poland)," *Waste Management & Research*, 38(11), pp. 1231–1238. Available at: https://doi.org/10.1177/0734242X20938448.

Karaban, K. *et al.* (2023) "The determination of microplastic contamination in freshwater environments using sampling methods: A case study," *Journal of Water and Land Development*, 57, pp. 140–146. Available at: https://doi.org/10.24425/jwld.2023.145344.

Kiełtyk, P. *et al.* (2024) "Sources affecting microplastic contamination in mountain lakes in Tatra National Park," *Resources*, 13(11), 152. Available at: https://doi.org/10.3390/resources13110152.

Klein, M., Worch, E. and Knepper, T.P. (2015) "Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany," *Environmental Science & Technology*, 49(10), pp. 6070–6076. Available at: https://doi.org/10.1021/acs.est.5b00492.

Koelmans, A.A. *et al.* (2019) "Microplastics in freshwaters and drinking water: Critical review and assessment of data quality," *Water Research*, 155, pp. 410–422. Available at: https://doi.org/10.1016/j.watres.2019.02.054.

Krajewski, A., Hejduk, A. and Hejduk, L. (2022) "First evidence of microplastic presence in bed load sediments of a small urban stream in Warsaw," *Sustainability*, 14(23), 16017. Available at: https://doi.org/10.3390/su142316017.

Lebreton, L.C. *et al.* (2017) "River plastic emissions to the world's oceans," *Nature Communications*, 8(1), 15611. Available at: https://doi.org/10.1038/ncomms15611.

Li, T. *et al.* (2023) "Research status and prospects of microplastic pollution in lakes," *Environmental Monitoring and Assessment*, 195(4), 485. Available at: https://doi.org/10.1007/s10661-023-11043-w.

Lin, H.T. *et al.* (2024) "Microplastics in Asian rivers: Geographical distribution, most detected types, and inconsistency in methodologies," *Environmental Pollution*, 349, 123985. Available at: https://doi.org/10.1016/j.envpol.2024.123985.

Liu, R.P. *et al.* (2021) "Microplastic pollution in surface water and sediments of Qinghai-Tibet Plateau: Current status and causes," *China Geology*, 4(1), pp. 178–184. Available at: https://doi.org/10.31035/cg2021011.

Mani, T. *et al.* (2015) "Microplastics profile along the Rhine River," *Scientific Reports*, 5(1), 17988. Available at: https://doi.org/10.1038/srep17988.

Meng, Y., Kelly, F.J. and Wright, S.L. (2020) "Advances and challenges of microplastic pollution in freshwater ecosystems: A UK perspective," *Environmental Pollution*, 256, 113445. Available at: https://doi.org/10.1016/j.envpol.2019.113445.

Mierzyńska, K. *et al.* (2024) "Traffic intensity as a factor influencing microplastic and tire wear particle pollution in snow accumulated on urban roads," *Water*, 16(20), 2907. Available at: https://doi.org/10.3390/w16202907.

Nava, V. *et al.* (2023) "Plastic debris in lakes and reservoirs," *Nature*, 619(7969), pp. 317–322. Available at: https://doi.org/10.1038/s41586-023-06168-4.

Nocoń, W.K. *et al.* (2023) "Changes in the microplastic content depending on the changes in the river catchment development structure–preliminary studies," *Desalination and Water Treatment*, 305, pp. 81–87. Available at: https://doi.org/10.5004/dwt.2023.29641.

Nocoń, W., Moraczewska-Majkut, K. and Wiśniowska, E. (2018) "Microplastics in surface water under strong anthropopression," *Desalination and Water Treatment*, 134, pp. 174–181. Available at: https://doi.org/10.5004/dwt.2018.22833.

Nocoń, W., Moraczewska-Majkut, K. and Wiśniowska, E. (2020) "Microplastics upstream and downstream dam-reservoirs," *Desalination and Water Treatment*, 199, pp. 263–272. Available at: https://doi.org/10.5004/dwt.2020.26026.

Pan, T. *et al.* (2023) "Review of microplastics in lakes: Sources, distribution characteristics, and environmental effects," *Carbon Research*, 2(1), 25. Available at: https://doi.org/10.1007/s44246-023-00057-1.

Panno, S.V. *et al.* (2019) "Microplastic contamination in karst groundwater systems," *Groundwater*, 57(2), pp. 189–196. Available at: https://doi.org/10.1111/gwat.12862.

Peng, X. *et al.* (2018) "Microplastics contaminate the deepest part of the world's ocean," *Geochemical Perspectives Letters*, 9(1), pp. 1–5. Available at: https://doi.org/10.7185/geochemlet.1829.

Piskuła, P. and Astel, A.M. (2022) "Microplastics occurrence in two mountainous rivers in the lowland area – a case study of the Central Pomeranian Region, Poland," *Microplastics*, 1(1), pp. 167–185. Available at: https://doi.org/10.3390/microplastics1010011.

Plastics Europe AISBL (2024) *Plastics – The fast facts 2024*. Brussels. Available at: https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024 (Accessed: July 28, 2025).

Plastics Europe Poland Foundation (no date) *Branża tworzyw sztucznych 2024. Raport Fundacji PlasticsEurope Polska [Plastics Industry 2024. Report by the PlasticsEurope Poland Foundation]*. Warszawa. Available at: https://plasticseurope.org/pl/wp-content/uploads/sites/7/2024/09/Raport-roczny-Fundacji-PlasticsEurope-Polska-2.pdf (Accessed: May 23, 2025).

Pol, W. *et al.* (2022) "Spatial-temporal distribution of microplastics in lowland rivers flowing through two cities (NE Poland)," *Water, Air, & Soil Pollution*, 233(4), 140. Available at: https://doi.org/10.1007/s11270-022-05608-7.

Pol, W. *et al.* (2023a) "Litter per liter – Lakes' morphology and shoreline urbanization index as factors of microplastic pollution: Study of 30 lakes in NE Poland," *Science of The Total Environment*, 881, 163426. Available at: https://doi.org/10.1016/j.scitotenv.2023.163426.

Pol, W. *et al.* (2023b) "No trophy for the trophy? – How lake trophy impacts bacterial assemblages of biofilm on microplastic," *Ecohydrology & Hydrobiology*, 23(4), pp. 602–613. Available at: https://doi.org/10.1016/j.ecohyd.2023.08.013.

Połeć, M. *et al.* (2018) "The occurrence of microplastics in freshwater systems – preliminary results from Krakow (Poland)," *Geology, Geophysics and Environment*, 44(4), pp. 391–400. Available at: https://doi.org/10.7494/geol.2018.44.4.391.

Reineccius, J., Bresien, J. and Waniek, J.J. (2021) "Separation of microplastics from mass-limited samples by an effective adsorption technique," *Science of Total Environment*, 788, 147881. Available at: https://doi.org/10.1016/j.scitotenv.2021.147881.

Rogowska, W. *et al.* (2021) "Microplastics in coastal sediments of Ełckie Lake (Poland)," *Studia Quaternaria*, 38(2), pp. 109–116. Available at: https://doi.org/10.24425/sq.2021.136827.

Rytelewska, S. and Dąbrowska, A. (2022) "The Raman spectroscopy approach to different freshwater microplastics and quantitative characterization of polyethylene aged in the environment," *Microplastics*, 1(2), pp. 263–281. Available at: https://doi.org/10.3390/microplastics1020019.

Schmidt, C. *et al.* (2020) "Microplastic particle emission from wastewater treatment plant effluents into river networks in Germany: Loads, spatial patterns of concentrations and potential toxicity," *Science of The Total Environment*, 737, 139544. Available at: https://doi.org/10.1016/j.scitotenv.2020.139544.

Sekudewicz, I., Dąbrowska, A.M. and Syczewski, M.D. (2021) "Microplastic pollution in surface water and sediments in the urban section of the Vistula River (Poland)," *Science of The Total Environment*, 762, 143111. Available at: https://doi.org/10.1016/j.scitotenv.2020.143111.

Sighicelli, M. *et al.* (2018) "Microplastic pollution in the surface waters of Italian Subalpine Lakes," *Environmental Pollution*, 236, pp. 645–651. Available at: https://doi.org/10.1016/j.envpol.2018.02.008.

Souza Machado de, A.A. *et al.* (2018) "Microplastics as an emerging threat to terrestrial ecosystems," *Global Change Biology*, 24(4), pp. 1405–1416. Available at: https://doi.org/10.1111/gcb.14020.

Strojny, W., Gruca-Rokosz, R. and Cieśla, M. (2023) "Preliminary study of the occurrence of microplastics in the sediments of the Rzeszów reservoir using the laser direct infrared (LDIR) method," *Sustainability*, 15(24), 16653. Available at: https://doi.org/10.3390/su152416653.

Talvitie, J. *et al.* (2017) "Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies," *Water Research*, 123, pp. 401–407. Available at: https://doi.org/10.1016/j.watres.2017.07.005.

Tarasewicz, K. *et al.* (2025) "A threat beneath the surface: Microplastic contamination in the groundwater of one of Europe's largest wetland complexes," *Science of The Total Environment*, 976, 179329. Available at: https://doi.org/10.1016/j.scitotenv.2025.1793299.

Thompson, R.C. *et al.* (2009) "Our plastic age," *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364 (1526), pp. 1973–1976. Available at: https://doi.org/10.1098/rstb.2009.0054.

Thompson, R.C. *et al.* (2024) "Twenty years of microplastic pollution research – what have we learned?," *Science*, 386(6720), eadl2746. Available at: https://doi.org/10.1126/science.adl2746.

Waldschläger, K. *et al.* (2022) "Learning from natural sediments to tackle microplastics challenges: A multidisciplinary perspective," *Earth-Science Review*, 228, 104021. Available at: https://doi.org/10.1016/j.earscirev.2022.104021.

Yang, S. *et al.* (2022) "A comparative review of microplastics in lake systems from different countries and regions," *Chemosphere*, 286, 131806. Available at: https://doi.org/10.1016/j.chemosphere.2021.131806.

Zhang, K. *et al.* (2018) "Microplastic pollution in China's inland water systems: A review of findings, methods, characteristics, effects, and management," *Science of the Total Environment*, 630, pp. 1641–1653. Available at: https://doi.org/10.1016/j.scitotenv.2018.02.300.

Zima, P., Wielgat, P. and Cysewski, A. (2017) "The study of water pollution of the lower Vistula River by plastic particles," *International Multidisciplinary Scientific GeoConference: SGEM, Water Resources. Forest, Marine and Ocean Ecosystems*, 17, pp. 729–736.

Zolotova, N. *et al.* (2022) "Harmful effects of the microplastic pollution on animal health: A literature review," *PeerJ*, 10, e13503. Available at: https://doi.org/10.7717/peerj.13503.