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Review

Microplastics in Polish Inland Waters: Current Knowledge, Methodological Limitations, and Research Needs

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Abstract

Microplastics (MPs) are an emerging contaminant of concern in aquatic ecosystems, yet knowledge of their presence in Polish inland waters remains fragmented and limited. This review synthesizes the current state of research on MPs contamination in rivers, lakes, and groundwater in Poland, based on 33 scientific publications. It compiles reported contamination levels in various environments, including bottom sediments, wastewater, snow, tap water, and aquatic organisms, with a critical evaluation of the methodological approaches employed. Reported MPs concentrations in water samples ranged from 0 to 280 MPs/L, whereas in sediments, concentrations reached up to 120,000 MPs/kg, with rivers generally exhibiting higher contamination than lakes. Particular attention is given to sampling, extraction, and identification methods, which substantially influence the comparability and reliability of results. Furthermore, the review highlights key methodological gaps, such as the frequent reliance on visual identification and the lack of standardization across studies. We also present current research trends in Poland, identifying areas of growing interest and notable progress. These findings underscore the urgent need for harmonized methodologies and the establishment of a nationwide monitoring system to ensure robust assessment and management of MPs pollution in Poland's inland waters.

Keywords: plastic, emerging contaminants, freshwater, Poland, methodological limitations

Introduction

Plastic pollution is one of the most serious ecological challenges [1]. Global plastic production exceeds 400 million tons annually and continues to rise [2]. In Europe alone, 58.7 million tons of plastic were produced in 2022, with Poland ranking eighth in terms of production volume [2, 3]. A large portion of these materials are not recycled, but accumulate in the environment [4, 5]. Due to physical, chemical, and biological processes, larger plastic fragments break down to form microplastics (MPs), i.e., particles with a diameter of less than 5 mm [6]. MPs occur in various environmental compartments, including marine and inland waters, bottom sediments, soils, and animals [7], raising serious concerns about their impact on ecosystem functioning and human health [8, 9].

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Scientific interest in the presence of plastic in aquatic environments first emerged in the 1970s, primarily focusing on marine and oceanic ecosystems, where plastic pollution was first observed [10, 11]. For the following decades, research attention remained almost exclusively on marine environments [12]. The first study focusing on the presence of MPs in lakes was published in 2011, after which research on freshwater ecosystems increased [10]. In recent years, a particularly dynamic growth in research has been observed in China, which has led the world in the number of scientific publications in this field since 2018. The United Kingdom, the United States, and Germany have also shown considerable activity. Together with China, these countries are among the most influential in advancing MPs research in freshwater environments [13].

MPs have become the subject of intensive research throughout the European Union (EU), as evidenced by the growing number of scientific publications. However, despite this visible increase in research activity, comprehensive analyses are still lacking [14]. This gap is further exacerbated by the absence of appropriate standards [15]. Efforts are underway to develop standards, such as the technical report ISO/TR 21960:2020 (describing the environmental aspects and techniques used in MPs research) and the methodology established by Commission Delegated Decision (EU) 2024/1441, which defines procedures for measuring MPs in water intended for human consumption [16, 17]. The EUROqCHARM project also aims to evaluate and harmonize the methods used to study plastic pollution in the environment across Europe [18]. Despite these efforts, a universal and binding MPs monitoring system for inland waters in the EU remains in the conceptual phase.

In Poland, knowledge of MPs pollution in water remains limited, although the topic is attracting growing interest in the scientific community. Existing studies have confirmed the presence of MPs in both surface water and groundwater. In this context, particularly valuable are individual initiatives that attempt to organize existing knowledge and develop solutions applicable in practice. One example is the international FanpLESStic-sea project, carried out between 2019 and 2021 under the Interreg BSR programme, which aimed to reduce MPs emissions into the Baltic Sea and identify their sources. The project also included the development of standardized research methods [19].

Inland water MPs research continues to face serious challenges related to methodological inconsistency, which affects the comparability of results and their use in risk assessment [20]. The methodologies employed significantly impact the results, making meaningful comparisons between studies difficult. Differences exist at key stages, such as sampling, extraction, and the selection of analytical and identification techniques for suspected particles [21]. Some approaches also fail to provide representative data, further complicating efforts to assess the extent and dynamics of pollution [22]. A unified research methodology is urgently needed to enable long-term, comparable analyses [23].

Despite a growing number of studies documenting the presence of MPs in Polish inland waters, the overall picture remains incomplete and fragmented. Research to date has revealed generally low to moderate contamination levels, with notable local hotspots, particularly in rivers downstream of urban areas and wastewater treatment plants (WWTPs). At the same time, lakes tend to show lower concentrations. Recent years have seen increasing interest in assessing MPs occurrence not only in surface waters but also in sediments, groundwater, and biota, reflecting global trends toward understanding their pathways through the entire water cycle and food webs. However, methodological inconsistencies in sampling, extraction, and identification still reduce the comparability and reliability of results, often producing inconsistent or overestimated MPs contamination levels.

The main objective of this review is to synthesize the current state of knowledge on MPs pollution in Polish inland waters. In addition, it aims to: (i) summarize the findings of studies conducted so far and provide an overview of contamination levels reported in rivers, lakes, and sediments; (ii) identify current research trends and directions, highlighting areas that have gained attention in recent years; and (iii) critically evaluate methodological challenges that hinder reliable assessment of MPs contamination, with particular emphasis on the need for standardized approaches. Together, these insights are intended to support the development of more robust monitoring strategies and to guide future research priorities in this field.

Materials and Methods

This literature review is based on search results obtained from three academic databases: Google Scholar, Scopus, and Web of Science Core Collection (WoS-CC) [24-26]. The search was conducted using six keyword phrases: Microplastic Poland, Microplastic River Poland, Microplastic Lake Poland, Microplastic Inland Water Poland, Microplastic Freshwater Poland, and Microplastic Groundwater Poland. The searches were performed in January 2025 without applying a specific date range, thus covering all available publications retrieved by the databases.

Following the initial screening, 36 publications were initially identified as relevant. Three of these were excluded from further analysis for the following reasons: lack of direct reporting on MPs concentrations [27], data presented exclusively in mass-per-volume units without the possibility of conversion to particle count [28], duplication of content already covered in previously included articles [29].

The final set of analyzed publications included 33 studies, some of which focused directly on inland waters in Poland, while others addressed environments

closely related to freshwater ecosystems. The main aim of the review is to estimate microplastic contamination in rivers, lakes, and groundwater, as well as to present the associated methodological challenges.

In order to present MPs contamination levels, we extracted both concentration ranges and mean values from publications. When mean concentrations were reported for individual sampling sites, we calculated a single overall mean across all sites to summarize the data. If only raw data for individual samples were available, we computed both the mean and the range of concentrations directly from those values.

In studies including multiple water bodies of different types (e.g., several lakes and rivers), results were presented as separate group means for lakes and for rivers.

To ensure consistency and enable comparisons between studies, all MPs concentration data were converted to standardized units, depending on the type of environment analyzed. For liquid samples, such as surface water or wastewater, concentrations were expressed as the number of particles per liter (MPs/L). For solid materials, such as bottom sediments, values were converted to the number of particles per kilogram (MPs/kg). In the case of biological material, such as fish or amphibian larvae, the average number of microplastic particles per individual and the percentage of individuals in which microplastics were detected were calculated. This allowed for a more consistent interpretation of results despite differences in the way they were originally reported.

Results and Discussion

Microplastic Contamination in Polish Inland Waters

A review of the available literature shows that research on MPs in Polish inland waters began relatively recently, with the first studies published in 2017. In the following years, the number of studies on inland waters remained limited, with an increase from 2021 (Fig. 1), reflecting growing scientific interest in this topic. In total, 16 studies focused on the pollution of freshwater ecosystems, primarily rivers and lakes, and only two included groundwater. While most investigations focused on a single type of aquatic environment, some adopted a broader perspective by simultaneously examining multiple systems, such as rivers and lakes or rivers and groundwater. In one study, river water was analyzed together with sediments, providing insight into both vertical and horizontal MPs transport within catchment areas [30]. We also included 17 studies on related environments, including bottom sediments, wastewater, aquatic organisms, snow, tap water, and plant material, which are discussed separately in this review.

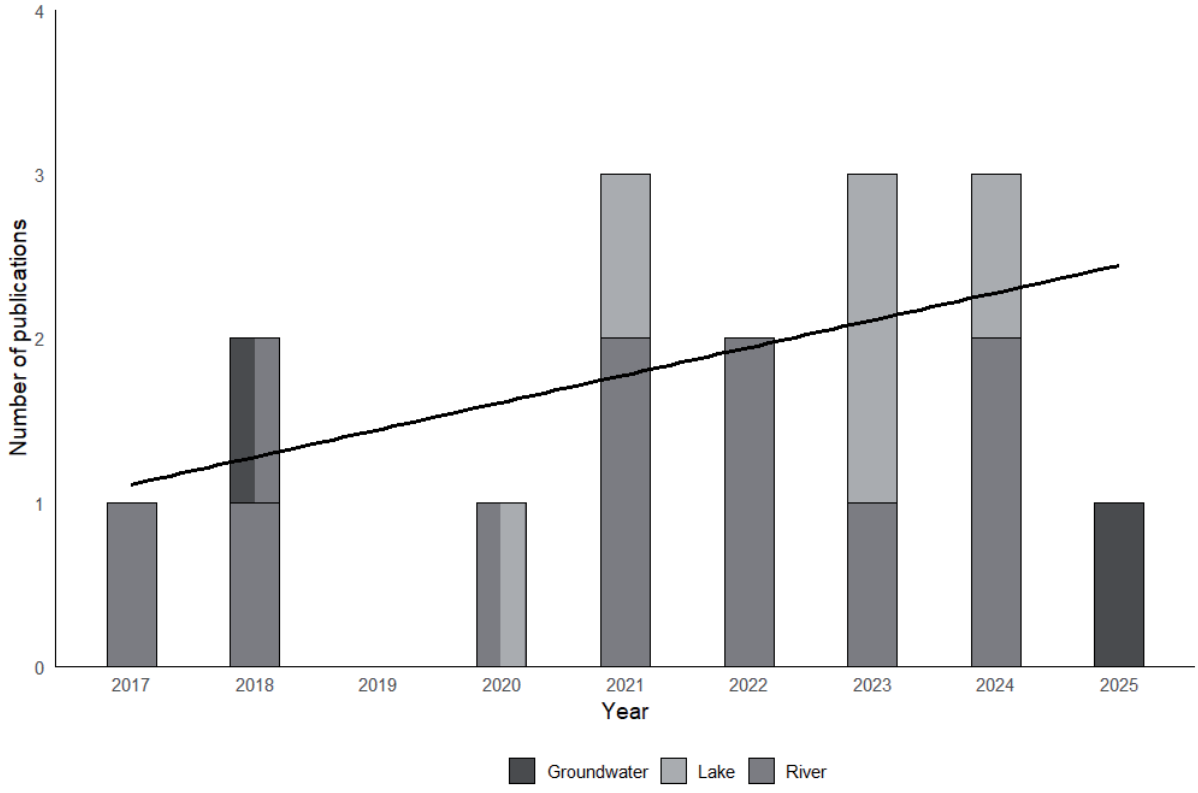

Fig. 1. Number of publications per year on microplastics contamination of Polish inland waters, categorized by the main type of ecosystems (lakes, rivers, and groundwaters). The black line indicates a linear trend in the number of publications over time.

Data on rivers were obtained from 11 papers covering a total of 18 rivers. Most of these studies reported low MPs concentrations, with mean values below 1 MPs/L in 12 cases (Table 1). One study documented moderate contamination, with two rivers showing mean concentrations of about 10 MPs/L [31]. In contrast, two publications reported exceptionally high levels, with mean values reaching 106.8 MPs/L [32] and 245 MPs/L [33].

The first Polish study by Zima et al. [34] confirmed the presence of particles resembling MPs in the Lower Vistula, with a concentration of 0.00011 MPs/L, however, this research was of a preliminary nature, aimed at testing and refining the methodology. The study from the Upper Vistula shows an increase in MPs content along the course of the river, with higher concentrations in the cities and downstream of the WWTP; however, the differences observed downstream of the WWTP were not significant [35]. Other research from the Upper Vistula from Kraków city pointed out the accumulation of MPs and mesoplastics (larger particles) in river backwaters [36] and proposes digital image analysis and multivariate data analysis as tools for the identification of MPs in surface waters [32]. The contamination by MPs of the middle course of the Vistula River (Warsaw city) ranged from 1.6 to 2.6 MPs/L. The highest MPs concentration was observed in the water collected in the city centre, and the lowest downstream of the WWTP [30]. This study pointed out the adsorption of various elements onto the MPs surface, and the adhered particles were confirmed by scanning electron microscopy [30]. The results from the Nida River (tributary of Upper Vistula) reported very high concentrations of MPs, with values ranging from 215 to 280 MPs/L and an average of 245±21 MPs/L. This research also emphasized the presence of heavy metals on MPs particles [33].

The research on three rivers in Upper Silesia revealed a constant presence of MPs with higher densities after cities and WWTPs [37]. The other results from Upper Silesia investigated the role of dam reservoirs in MPs removal, and the results showed that most plastic particles are accumulated in the area of the reservoirs [38]. Research by Połeć et al. [39] pointed out the presence of particles resembling MPs in two rivers in southern Poland, but qualitative analysis did not confirm the presence of synthetic polymers.

Pol et al. [31] studied two rivers flowing throughout two cities in north-east Poland and reported similar contamination of both rivers at a levels of about 10 MPs/L. The authors also claim that WWTPs was

Table 1. Microplastic concentrations in surface waters of Poland and applied methodologies.

Object	Number of water bodies	MPs range (MPs/L)	MPs mean (MPs/L)	Concentrated	Extraction	Verification	Ref.
L	2	0-3.1	—	Yes	Di, Fi	—	[22]
R	1	1.6-2.6	—	Yes	Si, Di, Fi	n, Ra, F	[30]
R	2	4.9-25.2	10.6	Yes	De, Fi	n	[31]
R	1	—	106.8	Yes	Di, De, Fi	n	[32]
R	1	215-280	245	No	Fi	—	[33]
R	1	—	0.00011	Yes	Fi, Di	—	[34]
R	1	0.002-0.017	0.007	Yes	Di, Fi	—	[35]
R	1	—	7	Yes	De, Fi, Di	n	[36]
R	3	—	0.04	Yes	Di	—	[37]
L	3	—	0.03	Yes	Di	—	[38]
R	3	—	0.02	Yes	Di	—	[38]
R	2	0	0	No	Fi	Ra	[39]
G	1	0	0	No	Fi	Ra	[39]
R	2	—	0.0008	Yes	Di, Fi	F	[40]
L	1	—	0.0002	Yes	Di, Fi	Ra	[44]
L	11	0-0.3	0.1	Yes	Di, Fi	Ra	[45]
L	30	0.2-1.6	0.8	Yes	De, Fi	n	[46]
G	102	0-14.1	1.3	Yes	Di	Ra	[47]

Abbreviations used: – data not reported. Waterbody type: R – river; L – lake; G – groundwater. Extraction: Di – digestion; De – density separation. Mechanical separation: Fi – filtration; Si – sieving. Verification method: n – hot needle test; F – FTIR; Ra – Raman spectroscopy.

the main source of MPs. The results from two rivers in northern Poland from the Pomeranian region may indicate lower contamination of MPs, which were present only in 62.5% of samples, but this study reported only the total number of particles in samples [40]. These authors also claim that WWTP was the main source of MPs, but the differences were small, close to statistical significance. Despite the often small or statistically insignificant differences in MPs concentrations upstream and downstream of WWTPs, a recurring pattern across numerous studies indicates that WWTPs are a likely and consistent source of MPs pollution in Polish rivers. WWTPs demonstrate relatively high efficiency in reducing MPs emissions. In the analyzed studies, MPs concentrations in untreated wastewater ranged from 2.7 to 552.5 MPs/L [41, 42], while locally, values in runoff from combined sewer systems reached up to 5,535 MPs/L. In treated effluent, concentrations ranged from 0.002 to 1 MPs/L, with one study reporting a mean of 0.49 MPs/L [41-43]. This substantial reduction suggests that the contribution of WWTPs to MPs pollution in surface waters may be limited.

MPs contamination of lakes was investigated in five publications, which together covered 47 lakes (Table 1). In all cases where mean MPs concentrations were reported, the values did not exceed 1 MPs/L, while higher concentrations referred only to maximum values, reaching 3.1 MPs/L. This suggests low levels of MPs contamination in the analyzed lakes and indicates that MPs concentrations in lakes tend to be lower than those observed in rivers. This is confirmed, among others, by the results of the study by Nava et al. [44], which showed that the Wdzydze reservoir is one of the least microplastic-contaminated among 38 water bodies located in different regions of the world [44]. Research conducted in 11 lakes located within a protected mountain area also reported low concentrations of MPs, confirming their presence even in relatively isolated and minimally disturbed environments [45]. Both studies employed reliable techniques for qualitative analysis, which increases the credibility of the results [44, 45]. Slightly elevated levels were observed in the study by Pol et al. [46], which included 30 lakes in the Masurian Lake District. Karaban et al. [22] examined two lakes in central Poland located on rivers, reporting only a range of MPs concentrations, with maximum values reaching 3.1 MPs/L, the highest among all lakes in this review. This lack of mean concentration data complicates direct comparisons with other studies.

Groundwater remains the least studied type of aquatic environment in terms of MPs contamination, with only two scientific publications (Table 1). In the study conducted by Połeć et al. [39], groundwater samples collected from a single well contained particles resembling MPs. Their shapes and colours suggested an anthropogenic origin, although polymer composition was not confirmed [39]. The second study conducted a large-scale investigation involving 102 wells in the Biebrza River Valley, detecting MPs in 101 samples, with concentrations ranging from 0 to 14.1 MPs/L [47]. No clear correlation was identified between MPs contamination and population density. Moreover, the findings indicate a spatially uneven distribution of MPs, which may be shaped by site-specific environmental factors in the vicinity of each well [47]. Despite the relatively high number of wells analysed, the availability of data on MPs in Polish groundwater remains very limited, which hampers nationwide interpretation and highlights the need for further methodologically consistent research in this field.

Microplastic Contamination in Bottom Sediments of Polish Inland Waters

MPs contamination in bottom sediments has been reported in five publications covering five lakes and two rivers in Poland. Higher concentrations of MPs were recorded in bottom sediments than in surface waters, which may be related to sedimentation processes dependent on particle density. Reported concentrations of MPs in lake sediments ranged from a minimum of 4 MPs/kg to mean values around 22 MPs/kg across two studies (Table 2). Nevertheless, one study reported much higher values from 7,500 to 120,000 MPs/kg, suggesting locally elevated concentrations of MPs in Rzeszów Reservoir. In the case of rivers, available data indicate concentration ranges from 190 to 9,300 MPs/kg (Table 2). These values are significantly higher than the average concentrations reported for lake sediments, which may reflect greater MPs accumulation in riverine environments [30, 48-51]. Although mean values were not provided in all studies, the available data suggest a higher level of contamination in river sediments. These findings should, however, be interpreted with caution due to the limited amount of available data, which highlights the need for further research in this area.

Microplastic Contamination in other Inland Water Habitats

MPs have also been found in unusual freshwater habitats, such as snow, wastewater, tap water, and aquatic organisms. Two publications have reported the presence of MPs in snow. One of these studies examined three mountain trails located in the Carpathians and the Sudetes, where the reported mean MPs concentrations ranged from 5.2 to 12.9 MPs/L. This study pointed to higher contamination levels on easier and more frequently used tourist trails, especially in their lower sections [52]. A similar trend was observed in a study on MPs in snow collected along urban roads. The authors analyzed the impact of traffic volume and reported statistically significant differences in mean concentrations, which ranged from 62.3 to 792.7 MPs/L, with higher particle counts observed on road sections with heavier traffic [53]. The study by Gajewska et al. [54] demonstrated

Table 2. Microplastic concentrations in sediments of Poland and applied methodologies.

Object	Number of water bodies	MPs range (MPs/kg)	MPs mean (MPs/kg)	Sampling	Extraction	Verification	Ref.
R	1	190-580	—	Sh	D, Si, Fi	n, Ra, F	[30]
L	3	4-21	11.3	U	De, Di, Fi	—	[48]
R	1	6367-9300	—	Sa	Si, De, Di, Fi	—	[49]
L	1	—	22	Sa	De, Di, Fi	—	[50]
L	1	7500-120000	—	—	De, Di, Fi	L	[51]

Abbreviations used: — data not reported. Waterbody type: R – river; L – lake. Sampling: Sa –sampler; Sh – shovel; U – UWITEC gravity probe. Extraction: Di – digestion; De – density separation. Mechanical separation: Fi – filtration; Si – sieving. Verification: n – hot needle test; F – FTIR; Ra – Raman spectroscopy; L – LDIR.

that stormwater runoff from urban areas delivers extremely high loads of MPs, with concentrations ranging from 1,400 to 14,036 MPs/L.

Another identified study addressed the issue of secondary contamination of tap water with MPs in the Upper Silesian Agglomeration. Tap water samples were collected from three points, one supplied by surface water and two by groundwater. The mean MPs concentration was 0.1 MPs/L in tap water from the surface source, and 0.1 MPs/L and 5.8 MPs/L at the two groundwater-sourced points. The scope of this study did not allow for a precise determination of the origin of MPs detected in the tap water. The authors suggest that contamination may originate from inland waters or other stages of the water supply system, such as the distribution network or internal installation. Further detailed studies are necessary to fully clarify the sources and mechanisms of MPs transport within water supply systems [55].

The presence of MPs has also been confirmed in freshwater fish. In a study conducted in southwestern Poland, 202 gudgeons *Gobio gobio* (Linnaeus, 1758) and 187 roaches *Rutilus rutilus* (Linnaeus, 1758) were examined. Microplastic-like particles were detected in 54.5% of gudgeons and 53.9% of roaches. The mean number of particles per individual was 1.2 for both gudgeons and roaches [56]. The other paper reported that MPs were detected in 74 out of 123 specimens, which corresponds to 60.2% of all fish examined, based on the analysis of the gastrointestinal tract, liver, and gills. An average of 1.8 MPs particles per individual was found, with no correlation with body size [57]. Previous analyses of water from the same locations revealed MPs concentrations at the level of 0.0008 MPs/L. Although these values confirm the presence of MPs in the environment, the higher amounts found in organisms may result from the accumulation of MPs or an increase in contamination levels over the years [40]. The authors noted that limiting the analysis to selected organs does not allow for a full assessment of the MPs burden. Although not all of the studied species are commonly consumed, those that do enter the human diet may represent a potential route of MPs exposure [56, 57]. These findings point to the accumulation of MPs within the aquatic food web.

Two additional studies reported the presence of MPs in amphibian larvae in western Poland. In the first study, MPs were detected in 53 out of 201 individuals, accounting for 26% of the sample, with an average of 0.4 particles per larva [58]. In the second study, MPs were detected in 663 out of 914 examined amphibian larvae, representing 73% of the individuals, with an average of 1.8 particles per individual [59]. The larvae originated from ditches, ponds, and puddles, from which water and sediment samples were also collected, revealing similarities in MPs shape and color [60]. MPs were also detected in spherical plant-based formations, known as lake balls, found in northern Poland. These structures, composed of densely compacted plant material, contained small invertebrates as well as MPs particles. Their contamination suggests that such benthic formations may play a role in the local retention of MPs in freshwater ecosystems and could serve as potential indicators for assessing plastic pollution levels in aquatic environments [61].

Methodological Problems – Sampling

The methodology used for water sampling has a direct impact on the number of MPs particles detected and the overall quality of the resulting data. Both the sampling technique and the volume of water analyzed determine the effectiveness of detection and the feasibility of sample collection [21, 62, 63]. In the reviewed studies, three main approaches can be distinguished: collecting a specific volume of water into a container without concentration, filtration through a plankton net or sieve after collection, and net towing along the water surface.

The simplest method is sampling directly into bottles, typically used when high contamination is expected [64, 65]. In this case, small volumes of water are collected without a pre-concentration step, which makes the procedure straightforward; however, the small sample volume negatively affects the representativeness of the results, especially in less contaminated

waters [65-69]. When lower concentrations of MPs are anticipated, more robust approaches involving pre-concentration by filtering larger water volumes through sieves or nets [70, 71]. In such cases, tens of liters are pumped or collected into a calibrated container and then passed through filters or meshes of defined size, allowing for the retention of MPs [30, 31, 46, 47, 72]. A third, comparatively less precise, yet commonly used approach is sampling by towing plankton nets through the water column, typically just below the surface [30, 68, 73]. While this method allows for the filtration of large water volumes and is widely used in marine and freshwater studies, it also introduces significant sources of error [68, 74]. Sample volume is often underestimated as a result of net clogging and unstable flow conditions [22].

The mesh size of the net is a critical factor determining the detectability of smaller MPs particles; those smaller than the mesh retention threshold can freely pass through, leading to substantial underestimation of concentrations [75]. This applies particularly to fibers, which, despite their considerable length, often have a very small diameter. Using smaller mesh sizes can improve recovery but increases the risk of clogging and requires additional care in quantifying filtered volumes [75, 76]. Therefore, careful selection of the sampling strategy and consideration of its limitations are crucial to obtaining reliable and comparable estimates of MPs contamination [21]. Harmonization of methodologies, particularly regarding sample volumes, mesh sizes, and pre-concentration procedures, remains an important goal for future studies [69, 77, 78].

In the reviewed studies conducted in Poland, both simple and more advanced water sampling techniques for MPs analysis were employed. In two cases, direct sampling into containers was used, with sample volumes not exceeding 5 L and without a pre-concentration step [33, 36, 39]. In one of these studies [36], no MPs were detected, which was likely due to the insufficient sample volume. However, the most common approach relied on plankton nets, which allowed for the filtration of significantly larger volumes of water. In six studies, water was first collected into calibrated containers and then filtered through plankton nets [30, 31, 32, 36, 46, 47], whereas in eight studies, plankton nets were towed through the water [22, 34, 35, 37, 38, 40, 44, 45]. In these cases, the volume of filtered water was substantially higher, and in some studies reached several tens of thousands of liters; however, towing also posed a risk of net clogging [22, 37, 44].

In six publications, the mesh sizes used ranged from 20 to 65 μm [30, 31, 40, 45-47], five studies applied a mesh size of 250 μm [32, 35, 37, 38], while one study used 500 μm mesh [34]. One study employed a set of nets with mesh sizes ranging from 20 to 500 μm [22] and in one case the mesh size was not reported [44]. To improve representativeness and maximize particle recovery, the use of smaller mesh sizes is recommended [74], which was confirmed by Karaban et al. [22], who recorded the highest MPs concentrations using the finest mesh nets. In three out of four studies that used a 250 μm plankton net, MPs concentrations did not exceed one particle per liter [35, 37, 38], which may be related to the fact that most particles likely passed through the mesh.

Plankton nets, which are a standard tool in such studies, are typically made of plastic, which introduces a risk of sample contamination with secondary MPs [79, 80]. For this reason, the use of plastic-based equipment is not fully recommended, especially in studies aimed at precise particle identification [80]. As an alternative, metallic sieves can be used, which eliminate the risk of contamination from the sampling tool. Rytelewska et al. [27] adopted this approach, employing a chromium-nickel stainless steel sieve that effectively removed both organic and inorganic contaminants from the samples before the analytical phase. In two studies, metal sieves were used in addition to plankton nets to retain particulate material and for size-based fractionation of MPs particles [30, 44].

The methods applied in Polish studies varied considerably in terms of sample volume, the type of equipment used, and the mesh size. Many of these approaches exhibited limitations that affected the quality and comparability of the results. In this context, sampling strategies based on known water volumes, followed by filtration through materials with the smallest possible mesh sizes, should be considered particularly valuable, as they allow for a more representative determination of MPs concentrations. Standardizing sampling procedures, including sample volumes and filtration parameters, remains essential for obtaining reliable and comparable data.

Another frequently analyzed aspect is spatial variability. In numerous studies, samples are collected from multiple locations within a single water body, allowing for the assessment of the distribution heterogeneity of MPs within a given ecosystem [30, 31, 33, 35-38, 41, 45]. For instance, Dacewicz et al. [36] demonstrated that differences between three sampling sites within the same reservoir were statistically significant, underscoring the importance of selecting appropriate sites. In many studies, samples were also collected during different seasons or months [31, 32, 35-38, 40], allowing for the analysis of seasonal factors. However, only a limited number of studies, such as those by Pol et al. [31], have attempted a systematic comparison of MPs concentrations across different time periods. In this case, seasonal differences in MPs levels were observed, reinforcing the relevance of the temporal dimension in interpreting results. Therefore, sampling strategies in MPs research should account for both spatial and temporal variability. Omitting either of these components may lead to incomplete, non-comparable, or potentially misleading data [21, 78, 81, 82].

Methodology Problems – Microplastic Extraction

The process of MPs extraction from environmental samples relies on techniques that enable effective separation of plastic particles from organic and mineral contaminants, while preserving the integrity of the MPs [81, 83, 84]. Proper sample preparation is critical for the accuracy of both quantitative and qualitative analyses [85]. In the reviewed studies, three main approaches were used: digestion, density separation, and filtration.

Digestion is one of the most commonly used sample preparation steps aimed at removing organic matter that may interfere with MPs analysis [21]. Among the 12 studies that applied digestion, oxidative methods were the most common, typically involving 30% H_2O_2 or Fenton's reagent (a mixture of H_2O_2 and $FeSO_4$). These reagents are widely used due to their high effectiveness in degrading a broad spectrum of organic material [86, 87]. However, prolonged exposure to elevated temperatures and high concentrations of H_2O_2 may lead to shrinkage and discoloration of MPs particles, making their identification more difficult [88-90]. In one study, a 20% HCl solution was applied following H_2O_2 treatment, and the procedure was demonstrated to effectively digest organic matter without damaging MPs particles [34]. In contrast, Karaban et al. [22] employed a mixture of 69% HNO_3 and 30% H_2O_2, which, although effective, entailed a higher risk of damaging sensitive polymers [91, 92]. Therefore, the selection of a suitable digestion reagent should always be preceded by preliminary testing to evaluate its efficiency and adjust the concentration to the specifics of the intended analysis [64]. In one study, enzymatic digestion with proteinase K solution was used to prepare samples for Raman spectroscopy [47]. This method does not degrade MPs [93].

In studies on sediments, apart from the reagents mentioned above, one study applied KOH following digestion with Fenton's reagent, which does not degrade most polymers, whereas another used NaClO, which may affect plastic properties; these details should be described in the methodology section [49, 51, 94, 95].

In four of the analyzed studies, density separation was used to isolate MPs from heavier organic and mineral components [31, 32, 36, 46]. This method is based on the assumption that most plastics are less dense than typical environmental sediments, allowing them to float in appropriately prepared density solutions [96]. A NaCl solution [32, 36] and a castor oil-based method [31, 46] were used in these studies. NaCl (density 1.17-1.20 g/cm^3) is inexpensive, readily available, and has minimal environmental impact; however, its low efficiency for higher-density polymers can limit recovery. Similarly, the low density of the castor oil method (0.96 g/cm^3) restricts its applicability to denser or contaminated microplastic particles [91, 96-99]. By contrast, sediment studies have employed denser solutions, such as $CaCl_2$ (density 1.37 g/cm^3) and K_2CO_3 (density 1.47 g/cm^3), alongside the standard reagents, enabling the recovery of a broader range of polymer types [51, 49, 91, 96, 98, 99]. Another limitation of density separation is the co-floating of light organic materials, which may rise along with plastic particles and distort results [100]. However, in most studies where density separation was applied, high concentrations of particles identified as MPs were recorded [31, 32, 36, 46].

In the reviewed studies, chemical digestion was the most frequent method, while density separation was used less frequently or combined with digestion in only a few cases. Preliminary removal of organic matter increases the accessibility of MPs and improves subsequent identification, which is why methods such as digestion, minimizing the risk of losing parts of the MPs fraction, are preferred.

Methodology Problems – Microplastic Filtration

Filtration using GF/C (or similar) filters was one of the most frequently applied MPs isolation techniques, reported in 13 of the analyzed publications [22, 30-36, 39-40, 44-46]. It constituted one of the final stages of sample preparation, with the primary function of retaining particles on the filter surface for further analysis [22, 30-36, 39-40, 44-46, 71, 101]. The retained MPs fractions depend directly on the pore size of the filter material used [102]. In four publications, no information was provided regarding pore size, which limits the ability to assess the effectiveness of the applied extraction method [31, 40, 46]. In the remaining studies, filters with pore sizes ranging from 0.4 µm to 1.6 µm were used. Filter pore sizes should not exceed 1 µm to ensure efficient capture of microplastics.

Methodology Problems – Verification

Accurate identification of MPs in environmental samples is a key stage in any study, as it determines the reliability of the obtained results [103]. Unfortunately, many analyses rely on visual methods or simplified procedures, such as the hot needle test, which do not guarantee reliable results [71, 104]. Spectroscopic techniques, which allow for unambiguous determination of chemical composition, are often omitted [105]. For example, in the study by Tarasewicz et al. [47], only 3% of visually selected particles were confirmed as MPs using Raman spectroscopy. Therefore, there is a high risk of misclassification and overestimation of contamination levels, which undermines the credibility of reported data and hinders comparison between studies [105, 106].

In six studies concerning MPs in aquatic environments, only visual analysis was used, employing optical, stereoscopic, digital, or fluorescence microscopy, without applying methods that could definitively confirm the synthetic nature of the particles (Table 1). While visual observation can serve as a helpful preliminary step for selecting suspected particles [107],

relying on it as the sole identification method carries a significant risk of misclassification [105]. This may lead to overestimated results and misidentification of natural fibres, organic fragments, or mineral particles as MPs [108]. Therefore, verification using reliable analytical techniques is essential for an accurate assessment of actual contamination levels [103].

In three of the analyzed publications [30, 33, 39], scanning electron microscopy (SEM) was used for MPs identification, enabling detailed assessment of particle surface morphology and potential degradation [33, 109, 110]. This technique, especially when combined with energy-dispersive X-ray spectroscopy (EDS), allows not only structural evaluation but also preliminary elemental analysis, which assists in distinguishing MPs from mineral or organic contaminants. Although SEM does not allow direct polymer identification, it can support visual verification protocols and help classify atypical or contaminated particles, while reducing the number of suspected items before spectroscopic verification [33, 111].

One of the methods for verifying the presence of MPs noted in Polish literature is the hot needle test, which was applied in five studies (Table 1). This technique involves applying a heated metal element to a suspected particle; a reaction such as melting, shrinking, or deformation may indicate the presence of plastic material [104]. Although this method is fast and inexpensive [112], its reliability as a tool for MPs identification is questionable [104]. One of its key limitations is the inability to determine the type of polymer [113]. Moreover, the method performs poorly when analyzing very small particles and may produce false positives, especially for some materials such as tire fragments, which do not melt or deform at the temperatures used in this test [104, 114]. For example, Lutz et al. [115] verified suspected particles using the hot needle method and subsequently analyzed those classified as MPs with μFTIR-ATR spectroscopy. It was shown that 51% of particles identified as MPs using the hot needle method were false positives, highlighting the low reliability of this technique [115]. Notably, many Polish studies (Table 1) that used the hot needle test as the main or sole identification method reported very high MPs concentrations. This may suggest that some of the results were overestimated due to incorrect classification of particles as MPs, which could result from the lack of chemical verification and the low selectivity of the method.

In five Polish studies, spectroscopic techniques such as FTIR (Fourier Transform Infrared Spectroscopy), Raman, and LDIR (Laser Direct Infrared) were applied, non-destructive methods enabling unambiguous identification of MPs and determination of polymer type based on characteristic molecular vibration spectra [105, 116, 117]. In Polish studies concerning inland waters, Raman spectroscopy has been the most commonly applied technique (Table 1). It is suitable for analyzing smaller particles and is characterized by relatively low sensitivity to water interference, which is a major advantage [118-120]. However, its use may be limited due to strong sample fluorescence and the need for prior sample preparation. By contrast, Fourier-transform infrared spectroscopy (FTIR) is more effective in the analysis of larger particles (typically >10-20 μm). It does not require sample pre-treatment, but its sensitivity to water necessitates complete drying of samples before analysis [117]. In the reviewed studies concerning inland waters (Table 1), those that applied spectroscopic techniques reported relatively low MPs counts, likely due to effective verification and the rejection of non-polymeric particles. However, in the study by Sekudewicz et al. [30], smaller MP particles were analyzed using Raman and/or FTIR spectroscopy. In contrast, larger ones were identified using the hot needle test, which may have negatively affected the results [30]. In one study focused on sediments, the LDIR technique was used [51], enabling rapid, automated analyses, particularly for particles too small to be reliably identified through visual methods [51, 121].

In international literature, gas chromatography coupled with mass spectrometry, especially pyrolysis-GC-MS (Pyr-GC-MS) and thermal extraction-desorption thermoextraction and desorption coupled with gas chromatography-mass spectroscopy (TED-GC-MS), is also indicated as a reliable approach to MPs identification [122]. These techniques allow for definitive identification of polymer type based on the characteristic products of thermal degradation [123] and offer high selectivity and sensitivity [92]. However, their main limitations are the destructive nature of the analysis, which involves breaking down the sample [124], and relatively high operational costs [125].

Many studies relied on visual analysis or the hot needle test for MPs identification, which increases the risk of misclassification and overestimation. Spectroscopic techniques like FTIR, Raman, and LDIR, though less frequently used, offer more reliable polymer identification. Internationally, gas chromatography-mass spectrometry methods are also applied for precise analysis. Wherever possible, spectroscopic or thermo-analytical techniques should be used to ensure accurate and verifiable results [105].

Conclusions

This review confirms that research on MPs pollution in Polish inland waters remains at an early stage, with currently available data being both limited and heterogeneous. Reported MPs concentrations in water samples showed considerable variability, while particle contents in bottom sediments were generally higher. However, the number of available studies focusing on sediments was smaller. This variability largely reflects the influence of local anthropogenic factors and the use of diverse methodological approaches, some of

which may have further affected the representativeness of the results.

The main limitation identified in the analyzed studies is the lack of methodological consistency, evident across all key stages from sample collection, through extraction, to particle identification. Differences were observed in sample volumes, mesh sizes of plankton nets, applied purification and separation methods, as well as analytical techniques. In many cases, visual inspection and the hot needle test were relied upon, which negatively affected the reliability and comparability of the data. Although spectroscopic techniques, such as FTIR and Raman spectroscopy, are being used with increasing frequency, they have not yet become standard practice. Standardization of methodologies is essential to improve the quality of future studies [23, 77, 78].

Considering these findings, the implementation of a national MPs monitoring system for inland waters is both justified and urgent. Such a system should be based on unified and comparable research.

Conflict of Interest

The authors declare no conflict of interest.

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