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Microplastic pollution in groundwater: a systematic review

Jin-Yong Lee[a], Jihye Cha[a], Kyoochul Ha[b] and Stefano Viaroli[c]

[a]Department of Geology, Kangwon National University, Chuncheon, Republic of Korea; [b]Groundwater Environment Research Center, Korea Institute of Geoscience and Mineral Resources, Daejeon, Republic of Korea; [c]Department of Earth Sciences, University of Pisa, Pisa, Italy

ABSTRACT

Groundwater, a crucial freshwater source faces increasing pollution from microplastics (MPs). This study aims to comprehensively review the aquifers, sampling and analysis methods, pollution levels, polymer types, and sizes of MPs in groundwater worldwide between 2017 and 2023. Very few reports exist on the abundance, polymer type, size, and other characteristics of MPs in the field. The tools, methods, and sample collection quantities used for field sampling varied considerably among studies. However, efforts to enhance our understanding of MP analysis results through groundwater level measurements, on-site water quality parameters, ion analysis, and field blanks have been limited. The analysis results mostly indicated higher concentrations in urban and industrial areas and landfill sites, whereas lower concentrations were observed in areas with minimal human influence. MPs in groundwater are predominantly polypropylene and polyethylene. Standardized sample collection and analysis methods are needed to further promote research on MPs in groundwater and facilitate cross-comparisons.

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1. Introduction

Groundwater is a vital resource important for various aspects of the environment and human life, as it is a crucial drinking water source for millions worldwide [1,2]. Groundwater accounts for 33% of all freshwater intake worldwide [3]. It is often of high quality because it is naturally filtered through soil and rock layers, reducing the risk of contamination compared to surface water sources including streams, rivers, lakes, and dams [4,5]. Groundwater also plays a fundamental role in agricultural activities, which consume about 70% of the global freshwaters especially for irrigation (approximately 90%) [3,6,7], which helps to sustain crop growth during dry periods, ensuring food security and agricultural productivity. Many industries rely on groundwater for their operations, such as manufacturing, energy production, mining, cooling systems, processing, and various industrial purposes owing to its reliability and relatively stable temperature [8,9].

In addition, groundwater maintains ecosystem health by providing base flow to rivers and wetlands, particularly during droughts or low-flow periods. It supports aquatic habitats, sustains vegetation, and contributes to biodiversity [10,11]. Groundwater is a crucial buffer during droughts or when surface water sources are limited. It can be accessed through wells, providing a reliable and relatively constant water supply and ensuring that communities can withstand periods of water scarcity [12,13]. Groundwater can also serve as an alternative source of clean water during emergencies such as floods or contaminated surface water events. It provides a backup supply for drinking, cooking, and sanitation, helping communities overcome immediate water-related challenges [14].

Groundwater storage can help mitigate the impacts of climate change, such as extended dry periods and altered precipitation patterns. Proper management and sustainable use of groundwater resources contribute to long-term water security and adaptation to changing climatic conditions [15,16]. Given its widespread availability and relatively untapped potential, sustainable use and management of groundwater resources are essential to ensure its long-term significance as a reliable water source for future generations. Increase in human pressure and the sources of contaminations may pose several concerns about aquifer protection, and the sources of contamination, especially the so-called 'emerging contaminants'.

In recent years, the issue of plastic pollution has gained significant attention worldwide due to its detrimental effects on ecosystems and human health [17–20]. Although the impacts of macroplastics, such as plastic bags and bottles, have been extensively studied and documented especially in marine environments [21–23], a relatively new concern has emerged about plastic pollution – microplastics (MPs) [19,24–26]. MPs are tiny plastic particles

CONTACT Jin-Yong Lee hydrolee@kangwon.ac.kr
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measuring less than 5 mm in size and are now recognized as pervasive and persistent pollutants in various environmental compartments, including marine and freshwater ecosystems [17–20]. A growing body of evidence suggests that MPs also infiltrate groundwater systems, raising serious concerns about their potential consequences for the environment and human well-being [17,27,28].

Historically, groundwater contamination research has focused on chemical pollutants, such as heavy metals, nitrates, petroleum hydrocarbons, and pesticides [29–32]. However, the recent discovery of MPs in groundwater has introduced a new dimension to the contamination landscape, posing unique challenges and complexities for environmental management [33]. The entry pathways of MPs into groundwater are numerous and interconnected. Surface runoff, agricultural activities (fertilizers and compost), atmospheric deposition, and wastewater effluents are among the primary sources of MPs entering groundwater systems [17,20,34]. These particles travel considerable distances and infiltrate aquifers, leading to accumulation in subsurface environments [35]. Once present in groundwater, MPs may persist for extended periods because of their inherent resistance to degradation, potentially resulting in long-term contamination and subsequent exposure [36].

The implications of groundwater MP pollution are multifaceted, affecting ecological integrity and human health. In ecosystems, MPs can adversely affect the soil structure, impair nutrient cycling, and alter microbial communities, ultimately influencing the overall functionality and resilience of groundwater-dependent ecosystems [36–38]. Furthermore, MPs can serve as vectors for transporting harmful chemicals and pathogens, exacerbating their potential ecological consequences [39]. Concerns regarding the human health implications of MP groundwater contamination are increasing [40,41]. Emerging evidence suggests that humans may be exposed to MPs by consuming contaminated groundwater or indirectly through food chains that rely on affected water sources [41,42]. The potential health risks associated with MPs include physical damage to organs, the absorption of chemical additives present in plastic, and the transmission of pathogens [43–45]. However, the full extent of these health risks and their long-term consequences requires further investigation.

This article aims to provide a comprehensive and comparative review of the current state of knowledge regarding MP pollution in groundwater, including its worldwide abundance, investigated aquifers, sampling volumes and methods, counting and identification methods, and polymer type and sizes [46]. Previous reviews focused on summary, sources and risks of MPs in groundwater [46–48]. This review contributes to a better understanding of this emerging environmental concern by synthesizing existing research and identifying methodological gaps in sampling, treatment and analysis. It informs that future research endeavors should be finalized toward: the definition of standardize the procedures and methods for collecting groundwater samples in the field (I), the identification of the MPs pathways toward and inside the aquifers (II), and mitigation strategies to safeguard groundwater resources (III) and promote a sustainable future.

2. Methods

We accessed the Web of Science database in June 2023 and followed the methods described below to explore the global research trends on MPs in groundwater and gather detailed information on MPs in actual groundwater samples.

We chose the Web of Science database because of its extensive coverage of scientific literature across various disciplines, including hydrogeology, hydrogeochemistry, and environmental science. The keywords 'microplastics' and 'groundwater' were selected as the primary search terms. These keywords were considered essential for retrieving relevant articles and studies related to MPs in groundwater samples.

We conducted a search using selected keywords in the database search interface within the title, abstract, and keyword fields to retrieve relevant articles comprehensively. In addition, the search was limited to articles written in English. Additionally, we focused on studies that specifically addressed MPs in groundwater samples and filtered out studies that discussed MPs in other contexts or media.

After completing the search ($n = 201$), pertinent information was extracted from the retrieved articles. These include title, authors, abstract, publication year, methodology, findings, and any relevant analytical techniques employed in the study. We analyzed the extracted data to identify global research trends in MPs in groundwater. This analysis examined the publication patterns, geographical distribution of studies, predominant research methodologies, and key findings.

A subset of 24 experimental articles describing the results of field activities were identified. We examined the methodologies employed for sample collection, MP extraction, identification, and quantification. We also analyzed the characteristics of the detected MPs, including size, shape, polymer composition, and abundance. The findings of the data analysis and detailed information on MPs in groundwater are summarized and presented in a suitable format, such as tables, graphs, or descriptive summaries.

By following this methodological approach, we aimed to gain insights into the global research trends on MPs in groundwater, extract detailed information about MPs in actual groundwater samples from the

Web of Science database, and we suggest future research directions and recommendations to secure more reliable MP analyses and remediation and management strategies.

3. Results and discussion

3.1. MPs in groundwater: bibliometric analysis

We identified 201 research papers from the Web of Science database. Starting with two papers published in 2017, the number of published papers has steadily increased over the years (Figure 1). However, despite increasing public grievances and interest in MP contamination in the environment, the number of research studies focusing on MPs in groundwater is not as high as expected [19,20]. The relatively low number of studies on MPs in groundwater can be attributed to the fact that groundwater is hidden beneath the surface, making it difficult for people to easily perceive the pollution caused by MP, despite the widespread presence of plastic waste on the ground surface. Therefore, the government and environmental authorities are also limited, and MP investigations and research investments are prioritized less than marine and surface water bodies [19,49]. Furthermore, the lack of universal and standardized methods, such as ISO guidelines, for sample collection (volume), procedures, and on-site pretreatment methods specifically tailored for MP analysis in groundwater also partially contributes to the limited research interest [17,19]. Nevertheless, despite these challenges, few researchers have conducted field surveys and laboratory experimental studies on MPs in groundwater [e.g [20,27,39,50]. This aligns with the international trend of plastic pollution reduction [51,52], and there is an expectation of significant interest and improvement in the near future.

Figure 2 shows the co-occurrence of key-words from the literature on MPs and groundwater. According to the 201 papers, the term 'microplastics' showed the closest relationship with 'groundwater', 'pollution', 'marine-environment', 'contamination', and 'nanoplastics', and deep associations with 'fate', 'water', 'transport', and 'adsorption' [17,19,20,24,26]. Furthermore, 'microplastics' strongly correlate with 'fresh water', 'soil', 'plastics', and 'degradation' [18,21,22,28]. However, it formed a group associated with 'particles', 'microplastic', 'waste water', 'drinking water', and 'identification' [23,27]. Through such associations, it is possible to understand the relationships between key terms related to MPs and we can figure out the changes in research interests and topics [33].

Figure 3 shows the co-authorship of the 201 papers represented by their affiliated countries. Only a limited number of countries have conducted MP studies on groundwater. The largest share was held by China ($n = 91$), followed by the Republic of Korea (Korea) ($n = 37$), the United States ($n = 28$), India ($n = 21$), Australia ($n = 20$), Germany ($n = 18$), the United Kingdom ($n = 14$), Italy ($n = 7$), the Netherlands ($n = 7$), and Mexico ($n = 6$). China has engaged in extensive research collaborations with India, Korea, and Canada (Figure 3(a)). In contrast, Korea has engaged in collaborative research with China, India, the United States, Germany, and Australia. The combined share of China and Korea exceeded half the total share (Figure 3(b)).

Although the presence of MPs is a problem on a global scale, we currently have experimental evidence of MPs in groundwater only in a few countries. While on the one hand the small number of articles published in these countries allows us to have only site-specific observations, what is noticeable is the complete lack of experimental studies in Africa, South

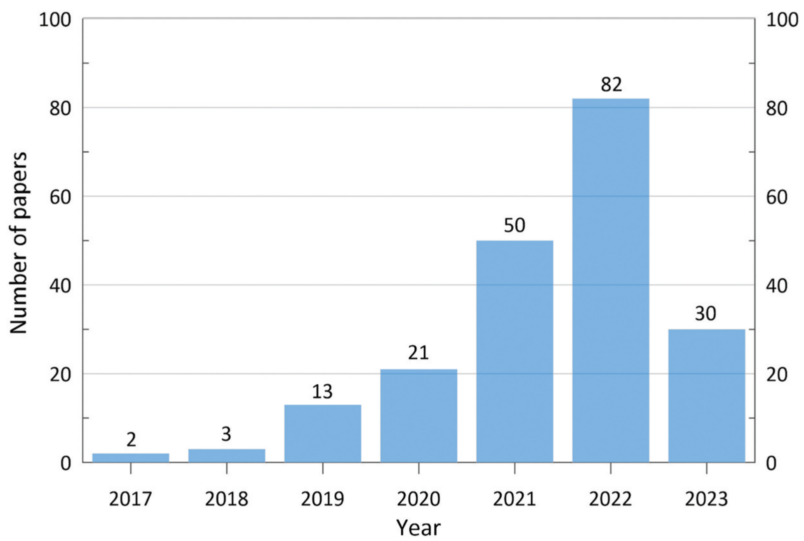

Figure 1. Number of MP studies in groundwater ($n = 201$) over the globe. The literature was retrieved from the Web of Science database in June 2023.

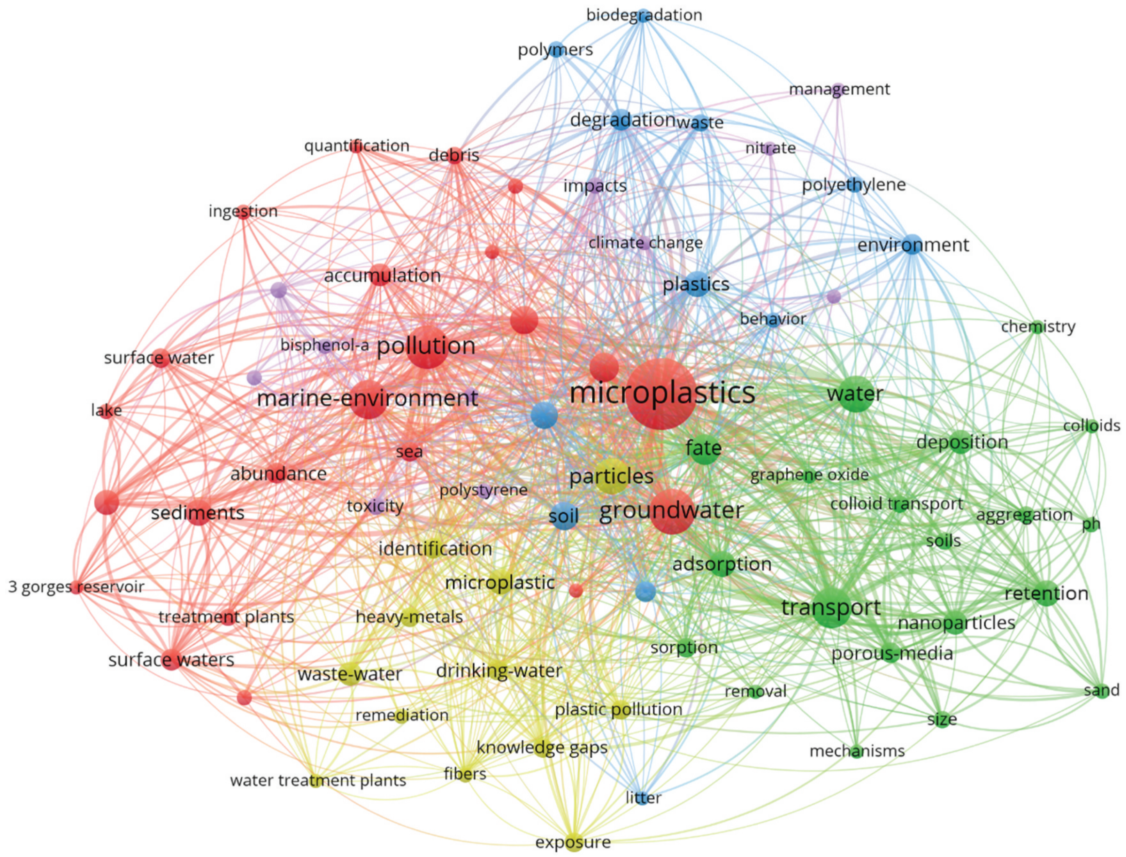

Figure 2. Co-occurrence of key words in MP studies in groundwater ($n = 201$) over the globe. The literature was retrieved from the Web of Science database in June 2023. This analysis was conducted by VOS viewer (www.vosviewer.com).

America and South East Asia. In these sectors are located the majority of developing communities that have large drinking water supply issues and that will suffer the most severe effects of climate change according to recent models [53]. This means that these populations will collect more and more contaminated or untreated water, also exposing themselves to the risk linked to the presence of MPs. Collaboration trends highlight how exchanges of knowledge and experience are more structured between the major global research centers. These lines of collaboration will have to open up in the near future towards collaboration, supervision and support of research also in developing countries.

A significant portion of these papers consisted of review articles ($n = 41$), and covered indoor laboratory test results. However, only a few cases have involved the analysis of MP concentrations in groundwater samples collected from actual field sites. A meticulous review of 201 papers identified 24 that provided data on MP concentrations in groundwater from field sites (review papers were excluded to avoid redundant inclusion). This study extracted and organized information on sampling methods, target aquifer, well depth, indoor analytical instruments, and data on MP concentrations, size, shape, and polymer types in groundwater (Table S1). The following sections present the results and discussion related to these findings.

3.2. Sampling and analysis methods for MPs detection

3.2.1. Characteristics of investigated aquifers and wells

Examining research on groundwater contamination by MPs, it is evident that there is limited hydrogeological information regarding the target aquifers. This may be because researchers with environmental science (engineering) or chemistry backgrounds are more interested in studying this issue than scholars specializing in hydrogeology [54]. However, despite this, it is evident that the surveyed aquifers were predominantly shallow, unconsolidated alluvial or karst aquifers [e.g [20,39,55–61]. This perception arises from the understanding that soils are readily exposed to sources of MP contamination from the atmosphere and the human activities on the ground surface. In contrast, in the case of groundwater, the penetration of MPs is perceived to be relatively lesser facilitated through the upper soil layers and the unsaturated section of the aquifer according to the MPs properties and environmental factors that may favor or contrast the underground mobility of the MPs [62]. As a result, shallow alluvial aquifers and karst aquifers, where the penetration of MPs is relatively easy, seem to have been the primary focus of initial investigations. A paper that formally introduced the occurrence of MPs in

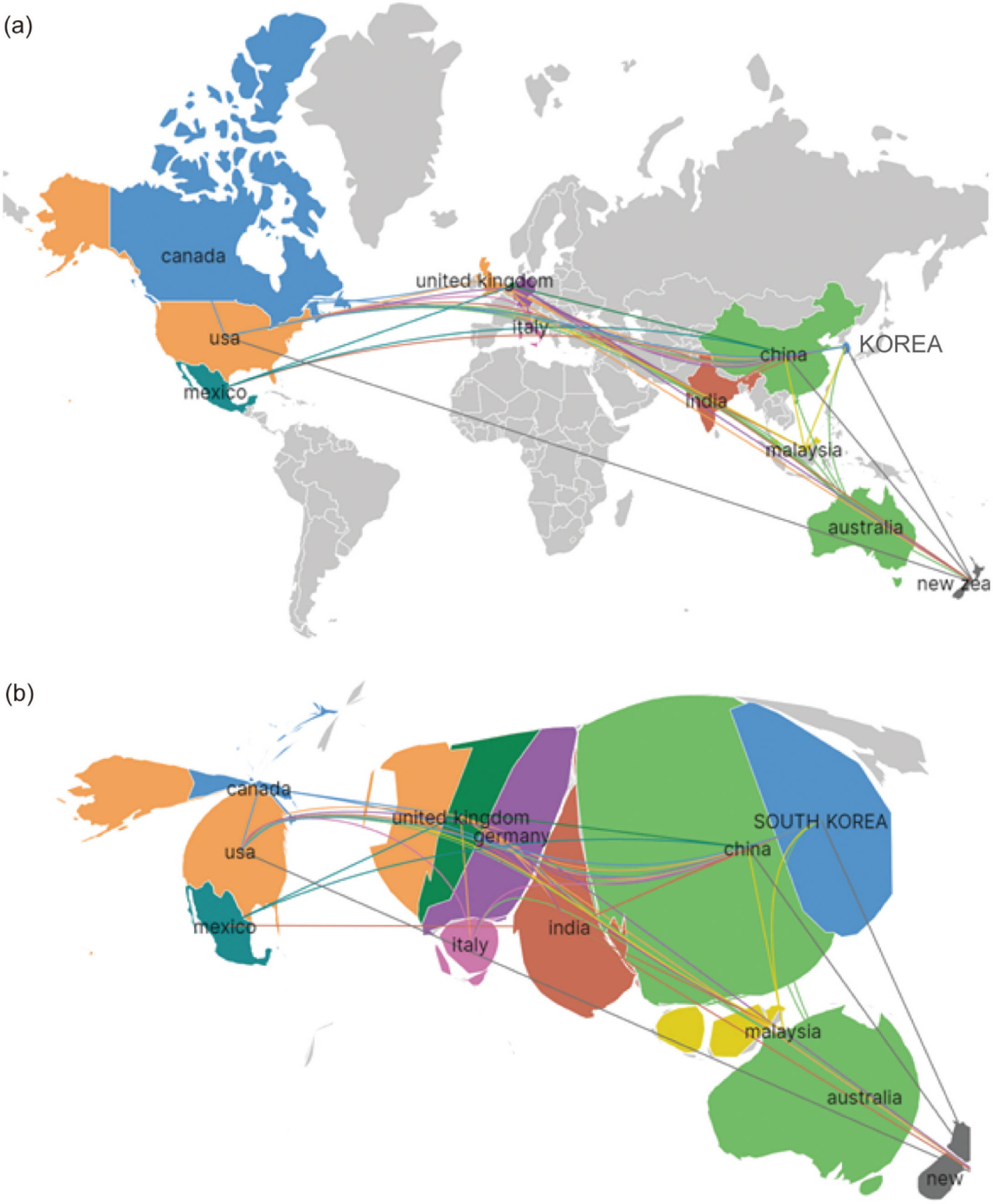

Figure 3. Co-authorships of MP studies in groundwater over the globe: (a) Distribution of countries and (b) Their weights. The data were retrieved from the Web of Science in June 2023. This analysis was conducted by VOS viewer (www.vosviewer.com).

groundwater in an international journal for the first time was a study on aquifers in Illinois, U.S.A. [55]. Moreover, investigations into MPs in shallow hand-dug open wells are still being conducted in countries such as India, Pakistan, and China [e.g [28,58]., because a significant amount of MPs is anticipated to be found in these shallower groundwater [54].

The depths of the investigated wells (except for spring and cave waters) ranged widely from 3 to 240 m (Table S1), ranging from very shallow groundwater readily affected by outdoor air and ground pollution sources to relatively protected bedrock groundwater. However, to date, there have been no concepts or schemes for examining vertical variations in MP abundance or comparing MP occurrence between shallow and deep groundwater. Rather, the wells and their depths appeared to have been selected randomly, as detecting MPs in groundwater was a priority. Excluding papers without information, researchers in Korea primarily conducted deep aquifer investigations compared to those in other countries, which mainly focused on studying shallow groundwater of 25 m or less.

Initially, investigations were conducted in well types that were either exposed to the atmosphere or surrounded by accumulated waste, such as spring water, cave water, or hand-dug wells (Table S1). Subsequently, research was conducted on wells with caps, such as drilled wells, drinking water wells, and capping wells, where there was no exposure to the atmosphere and better maintenance compared to hand-dug wells. This can be interpreted by initially focusing on areas with many pollution sources and anticipating a higher presence of MPs. After discovering MPs in such locations, the presence of MPs in groundwater from well types with fewer pollution sources and relatively good management was investigated [19,20]. Overall, the water levels varied from 0.16 to 143.2 m but in most cases, it is quite close to the ground surface. However, in some groundwater wells in China, the groundwater depths reached several tens of meters, and in Korea, they exceeded 100 m in some instances [50].

Most of the surveyed areas contained agricultural land. However, in some studies, there was a significant number of land uses, such as landfill sites, residential areas, and urban areas [57,58]. Because the types of plastics used can vary by land use, and some areas are more susceptible to surrounding pollution, it is expected that the types of MPs discovered may differ by land use.

3.2.2. Sampling and analytical methods

Most of the sampling (field campaigns) was conducted only once during dry or wet season. Only four studies, one from China conducted after 2021 and three from Korea, conducted sampling during both the dry and wet seasons (Table S1). However, it is important to determine the abundance and characteristics of MPs during both the dry and wet seasons [19,54]. Furthermore, even if the seasonal effect is not a concern, it is advisable to conduct multiple samplings because properly assessing the contamination status of MPs with just one sampling can be challenging and not representative. In each study (Table S1), the number of surveyed groundwater wells ranged from 2 to 81 (median = 7). The number of groundwater samples collected also ranged from 2 to 81 but the higher median value (= 12.5) highlight that some of the research are based on a seasonal monitoring with multiple samples collected in the same well. Currently, although sampling MPs in groundwater and analyzing them indoors is labor intensive and challenging [20], in the future, both the number of surveyed points should be increase and groundwater samples should be seasonally sampled to ensure a more reliable assessment.

Meanwhile, there are two methods for sampling MPs in groundwater: one involves pumping water and filtering it (pumping and filtering, also referred to as volume reduced sampling), while the other involves direct collection into bottles (grab sampling). When the samples volume exceeds 20 liters, the primary method employed was pumping and filtering, otherwise 1–2 liters grab samples were collected (Table S1). More than two-thirds of the studies primarily utilized grab sampling, mainly in areas with high concentrations of MP contamination. Conversely, larger sample volumes were collected from locations expected to have low contamination. However, when groundwater sample volumes are limited, biased results can arise regardless of the MP concentration [63]. Therefore, collecting a substantial quantity of groundwater is advisable for more reliable concentration evaluation [19,20,54].

Another concern is the use of plastic in the equipment and sample bottles used to collect groundwater samples. For instance, Teflon pumps, Polyvinyl Chloride (PVC) bailers, and PVC tubes were employed as equipment, whereas High Density Polyethylene (HDPE), Polyethylene (PE) containers, and Teflon-capped bottles were used as sample containers. Although some studies have conducted prior equipment cleaning and blank sampling, it is advisable to use equipment and sample bottles that do not contain plastics, such as glass and metal, when collecting MP samples [19,20,54].

However, less than half of studies also collected on-site groundwater quality parameters such as electric conductivity (EC), pH, temperature (T), dissolved oxygen (DO), oxidation-reduction potential (ORP), total dissolved solids (TDS), turbidity, and salinity. Investigating on-site parameters can be instrumental in understanding the sources and behavior of MP pollution; however, in many cases, this aspect is not well understood. Furthermore, ion analyses of groundwater have been conducted less frequently than on-site water quality parameter measurements. Only seven studies have performed ion analyses, and research examining major cations and anions is scarce, with only three studies in South Korea and one in India. Despite the importance of on-site water quality parameter measurements and ion analysis for understanding the occurrence and movement of MPs in groundwater, many researchers have not prioritized these aspects. These parameters and chemical compositions of groundwater affect substantially fate of MPs.

For the pre-processing of the MP analysis, two main methods were employed: digestion and density separation (see Table S1). The majority of studies utilized a solution of 30% H_2O_2 and Fe(II), with some studies using 15% H_2O_2. The most commonly used substance for density separation was NaCl, whereas others employed Li_2WO_4 (1.5 g/cm^3), $ZnCl_2$, or similar materials. Approximately one-third of the studies did not use any density separation while studies that did not use digestion are relatively rare. Additionally, staining, which involves the application fluorescence to distinguish MPs among various particles, has been conducted in only three studies. Three main tasks were performed to analyze the MPs: counting the number of MPs (or measuring their mass), analyzing their size, and classifying the types of MPs. These analyses primarily relied on the use of μ-FTIR (micro Fourier-transform infrared spectroscopy), optical stereo microscopes, Raman spectroscopy, LDIR (low-density infrared), and py-GC/MS (pyrolysis-gas chromatography/mass spectrometry). The first three instruments typically express the MP abundance in numbers, whereas the last quantifies it by mass.

Lab blanks are important when conducting MP analyses to eliminate potential cross-contamination from other sources and enhance accuracy. Of the studies, 62.5% used laboratory blanks, whereas the remainder did not. It is essential to conduct laboratory blanks to ensure the reliability of the analysis [20,54]. Field blanks serve as tools for assessing the external contamination that may occur during groundwater sampling in the field [19,20]. Less than half of the studies conducted field blanks; however, it is recommended to do so whenever possible to ensure the reliability of the analysis. Furthermore, information about purging should also be provided before sample collection. This is because purging has a significant impact on the concentration of MPs [61].

3.3. Abundance, polymer types and sizes of MPs

3.3.1. MPs abundance

Figure 4 shows the range of MP concentrations in groundwater across 24 case studies worldwide [64,65,66,67,68,69,70,71,72,73,74]. Globally, the MP concentrations ranged from 0 to 6,832 particles/L. The highest mean (or median) MP concentrations were found in the groundwater of five cities in Shandong Province, China. These sampling locations were very shallow, ranging from 4 to 8 m below ground surface, and were characterized by active industrial facilities and human activities in the vicinity. Additionally, the sample volumes were very small 0.6 L, which raises the possibility of overestimation [75].

The lowest concentrations of MPs in groundwater were found in South Korea. Despite significant agricultural use and sources of plastic pollution in these regions, groundwater wells are relatively well established and well managed, suggesting a limited inflow of plastic pollution. Furthermore, it is estimated that the relatively low MP concentrations are due to the large sample volume of 500 L, which is significantly higher than in other studies. However, as previously mentioned, quantitative comparisons are not straightforward because of the differences in sampling methods and sample volumes. The larger volumes resulted in lower MP concentration [63]. Nonetheless, regions with relatively high MP concentrations (AUS, CHI5, IND3, IND1, ITA1, and MEX2) were mostly characterized by unconfined aquifers and a high presence of pollution sources in the vicinity (see Figure 4). In addition, the sample volumes at these sites were very low (0.6–3 L). The impact of sample volume on the concentration of MPs needs to be further elucidated.

3.3.2. MPs composition and polymers

Figure 5 displays the polymer types of MPs found in groundwater across 24 studies worldwide based on field surveys. Overall, various types such as Polypropylene (PP), PE, Polyethylene Terephthalate (PET), Polystyrene (PS), Polyamide (PA), Polyurethane (PU), PVC, and Polyether sulfone (PES) were detected,

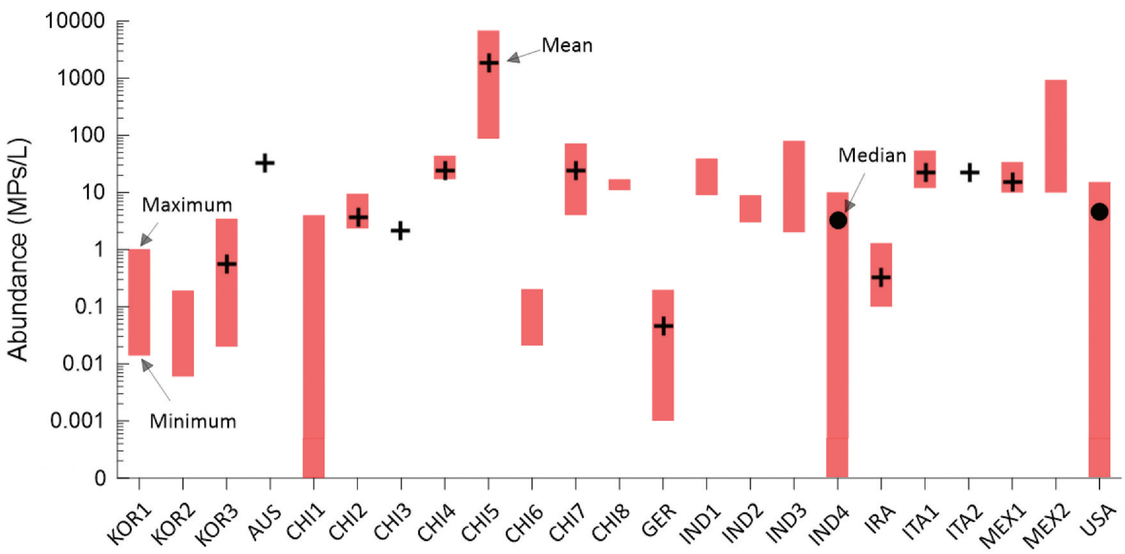

Figure 4. Abundance of MPs in groundwater at many countries in the world (KOR: Korea, AUS: Australia, CHI: China, GER: Germany, IND: India, IRA: Iran, ITA: Italy, MEX: Mexico, U.S.A.: United States of America). If the mean or median is unknown, it was not indicated (Table S1).

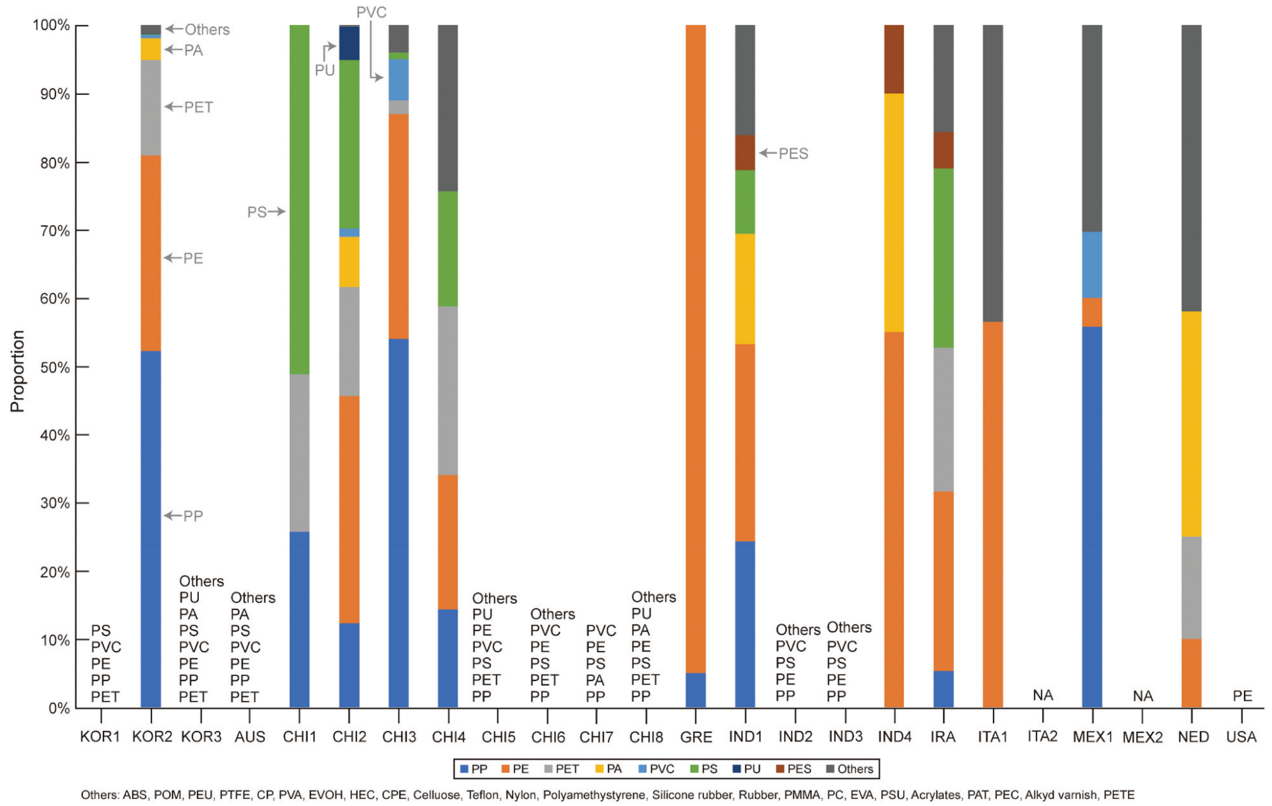

Figure 5. Polymer types of MPs in groundwater at many countries in the world. If the percentage is not known, only the polymer type was indicated and NA refers to cases where data is not available (Table S1).

with PP and PE being the most abundant. Their prevalence is likely due to their extensive use in agricultural areas for mulch, greenhouse films, shade nets, and fertilizer bags and their wide usage in industrial and urban areas for indoor decorations, clothing, food and cosmetic packaging, toys, furniture, and automotive parts. The 'Others' category in the graph includes polymers like Acrylonitrile Butadiene Styrene (ABS), Poly-Oxy-Methylene (POM), Poly Ester Urethane (PEU), Polytetrafluoroethylene (PTFE), Copolyester (CP), and Polyvinyl Acetate (PVA) when specific polymer ratios were not available and were represented in the text.

The region with the least variety of polymer types was Baden-Wurttemberg, Germany, where samples were collected from source water (groundwater) facilities for drinking water. Therefore, they appear to be less exposed to contamination, resulting in the detection of only PE and PP. However, more MP types have been found in groundwater from industrial and urban areas (such as CHI5). Furthermore, also significant diversity in polymer types was observed in the groundwater from agricultural and landfill areas (KOR3, IRA, CHI8, and AUS). Therefore, it can be inferred that the variety of plastic polymers in groundwater seems to be broader according to the land use, with a major variability in the urban areas where the most diverse plastic usage is accounted. Agricultural areas are whereas characterized by lesser variability in plastic polymers due to a more specialized use of plastic in the field activities.

3.3.3. Size distribution, shapes and colors

The size of MPs varies widely, ranging from approximately 10 micrometers to 5 millimeters, as shown in Table S1. The smallest sizes were believed to be limited by the constraints of the analysis, and even smaller MPs were expected. In general, smaller sizes were associated with higher counts. Relatively large MPs are frequently found in urban areas.

The observed shapes included fibers, fragments, foams, films, beads, pellets, spheres, rods, and fiber clusters. In most cases, fiber-shaped MPs were predominant, but fragments were much more common in rural groundwater in Korea. The prevalence of fiber-shaped MPs suggests human-induced activities in areas with a higher presence of fibers, mainly residential, industrial, and urban areas. However, identifying distinctive shape patterns based on land use remains challenging. MP colors vary widely and include black, gray, red, yellow, white, transparent, blue, green, and brown. Specific region-based patterns are difficult to discern.

4. Future research directions and recommendations

4.1. Standardized sampling approaches for MPs in groundwater

As mentioned earlier, the interest in and research on MPs has expanded from marine to terrestrial environments [1]. Research on MPs in soil and groundwater has recently gained increasing attention. Studies on MPs such as the fate and behavior of MPs in soil, the physical, chemical, and biological impacts of MPs on soil environment, and the impact of soil MPs on climate change, has been on the rise [19,36]. In contrast, research on groundwater, especially field studies, remains limited globally. One primary reason is that groundwater sampling is less straightforward than soil sampling. Groundwater sampling requires facilities such as boreholes, drilled wells, or open wells to collect samples. Moreover, aboveground or submersible pumps or bailers are needed to draw groundwater from certain depths, sometimes requiring additional electrical resources.

The biggest challenge is that there is currently no internationally agreed-upon method for collecting samples and standardizing procedures. There is no evaluation of the most appropriate tools for sample collection or research on the most suitable sample volume. Recent research has only focused on the impact of sample volume on the concentration and characteristics of MPs in groundwater [63]. The results showed that the sample volume significantly affected the concentration of MPs and the type of polymer present. Generally, it is recommended to use larger sample volumes (e.g. 500 L) in areas where low MP contamination is expected, and smaller volumes where contamination is presumed to be high [54,76]. However, these recommendations lack experimental support, resulting in researchers using varying sample quantities which makes comparing MP concentrations between studies nearly impossible. Therefore, a consensus and determination of the optimal sample quantity through multiple field investigations are necessary.

In addition, there is no agreement on whether purging is necessary before collecting samples, and if it so, the required amount of purging. Standardized methods applied in researches dealing with other groundwater contaminations, require pumping out the water already present in the wells before the sampling. This purging activity is necessary to avoid the sampling of stagnant water in the borehole, and usually the purge of 3–5 times the volume of this water is required just to be sure that the sampled water is representative of the real contamination and not the effect of the long-lasting interaction with the construction materials of the well. In many cases, the influence of purging on the evaluation of MP concentrations in groundwater is significant and crucial, as MPs may be initially removed from the groundwater. On the contrary, the direct groundwater sampling without purging may give more information of the exposure of the population that use the well to collect water for drinking or domestic uses.

Furthermore, field blanks are often used to assess the contamination caused by external factors when collecting groundwater samples in the field. However, further evaluation is required to determine whether this is necessary. Additionally, it is recommended to use non-plastic materials for sampling equipment, such as bailers, pumps, and various tools, to prevent contamination. However, plastic may inevitably be involved to some extent, and an evaluation is needed to determine how it truly affects the analysis results. A thorough assessment and investigation of these crucial factors are needed before standardized and agreed-upon procedures for sample collection in the field can be established.

As mentioned earlier, to assess the fate and behavior of MPs in groundwater, it is essential to obtain hydrogeological information about the aquifer in question [17,54,77]. However, until now, most efforts have primarily focused on quantifying the presence and identifying the types of MPs in groundwater, with insufficient investigation of these aspects. In the future, when conducting groundwater investigations for MPs, it will be imperative to consider a comprehensive analysis and understanding by measuring groundwater levels and field parameters of groundwater quality, and, if possible, conducting ion analysis related to the groundwater [78]. In particular, measuring groundwater levels at multiple points (wells) and conducting aquifer tests to determine parameters, such as hydraulic conductivity, are crucial. This information aids in understanding the flow direction and velocity of groundwater, which are essential for predicting the future behavior of MPs.

4.2. Knowledge gaps and areas requiring further investigation

In addition to research on the abundance of MPs in groundwater, research addressing the pathways through which the MPs enter the aquifer, along with their fate and behavior within, is currently lacking. First, in-depth studies are needed to understand the pathways through which MPs enter groundwater. It is commonly thought that MPs deposited through the atmosphere or directly introduced into the soil can vertically migrate and reach groundwater as the most fundamental pathway. However, empirical studies on the duration of such pathways, possible chemical and biological weathering or degradation during that time, and inflow rates (mass flux) at the interface are almost nonexistent. Furthermore, assessing MP inflow through river and groundwater interface areas, known as hyporheic zones, is necessary [79,80].

While there is a good understanding of the transport equations for typical dissolved substances in groundwater, it is essential to develop optimal transport equations for MPs using lab and field validation studies. While this has been attempted through modeling, there are still significant limitations [35,77]. This is crucial for evaluating and predicting how MPs found in groundwater move, at what rates, and through which kinetics they move. The challenge in assessing and predicting the behavior of MPs lies in the diversity of their sizes and polymer types, which can lead to variations in their behavior. Therefore, conducting theoretical and experimental studies of a wide range of polymer sizes and types is necessary.

Furthermore, concerns about the ecological and health impacts of MPs in groundwater, especially on animals and humans, arise from the adverse effects of MPs themselves and the concurrent presence of heavy metals, organic compounds such as PAHs, and antibiotics [18,20,27]. These substances can be adsorbed onto MPs, facilitating their transport through the aquifer and entry into the human body, which can have severe health implications. However, there is limited knowledge regarding how these substances attach to MPs, the extent of attachment, and their influence on the behavior of MPs. Therefore, substantial laboratory experiments and field investigations on these aspects are crucial. Parallel to the environmental studies on MPs, social research should be carried out to define the risk perception and to improve the awareness of MPs contamination in groundwater especially within the communities tapping more vulnerable aquifers, expanding the Socio-Hydrogeological approach [81,82].

4.3. Strategies for mitigating MP pollution in groundwater

Although research on MPs in groundwater is still in its early stages, it is necessary to develop methodologies to mitigate and purify MPs in aquifers. As the methods of investigation mentioned above and knowledge about the fate and behavior within aquifers accumulate, there will inevitably be a growing demand for pollution control. It is essential to block their entry pathways to reduce the presence of MPs in groundwater, underscoring the critical need for proper plastic management, particularly in soil and agricultural areas. Recently, there has been an increase in the development and use of biodegradable plastics; however, these may not be perfect alternatives and still have side effects and drawbacks [83]. Additionally, research is needed to determine methods and technologies for removing and remediating MPs that have already entered groundwater. Currently, one can consider basic physical methods, such as pumping and filtering groundwater containing MPs. However, it is essential to explore whether chemical or biological methods are available for in-situ removal [18,84,85].

However, there are many sources of MP pollution in our daily lives. For example, the application of technologies and washing machine techniques that generate fewer MPs during laundry considered one of the major sources of MPs, is required [86,87]. This should also involve the integration of technologies from other fields. Furthermore, efforts should be made to devise strategies to reduce the presence of MPs in effluents from wastewater treatment facilities, particularly because many effluents enter the ocean. Mitigation measures should be considered for groundwater adjacent to rivers, which can flow into groundwater by losing stream conditions in nearby hyporheic zones.

5. Conclusion

In this study, we have reviewed several international research trends, particularly field investigations, on MPs in groundwater. Although the interest in groundwater MP research is growing, a significant gap exists in our understanding. Given that groundwater is the source of drinking water for many people worldwide, the potential health risks associated with ingesting of MPs, alone or in combination with harmful substances, are of great concern. The following aspects require urgent research to address these issues effectively:

(1) First, there is a need to standardize the procedures and methods for collecting groundwater samples in the field. Currently, there is no internationally recognized method, making it challenging to compare and validate analysis results across different studies.
(2) It is essential to determine how MPs are introduced into aquifers and their sources, pathways, and kinetics. Quantitative assessments are necessary to understand the extent to which MPs enter groundwater through each pathway.
(3) Additionally, there is a need for research to assess the fate and behavior of MPs within aquifers, distinguishing them from typical dissolved substances. Modeling studies are crucial for predicting how MPs are distributed and moved, helping to understand their behavior within aquifers.
(4) Finally, various laboratory and field studies are needed to explore methods for reducing and remediating MPs that have entered groundwater. Therefore, urgent measures are required to alleviate concerns regarding the potential health impacts of MPs. Institutional and legal support is also necessary to promote the aforementioned investigations.

Groundwater microplastic pollution is a global phenomenon. Therefore, urgent research and investigation, as mentioned above, are necessary to ensure sustainable groundwater usage and safeguard human health from microplastic contamination in groundwater.

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Disclosure statement

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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