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Review article

Global status, risk assessment, and knowledge gaps of microplastics in groundwater: A bibliometric analysis

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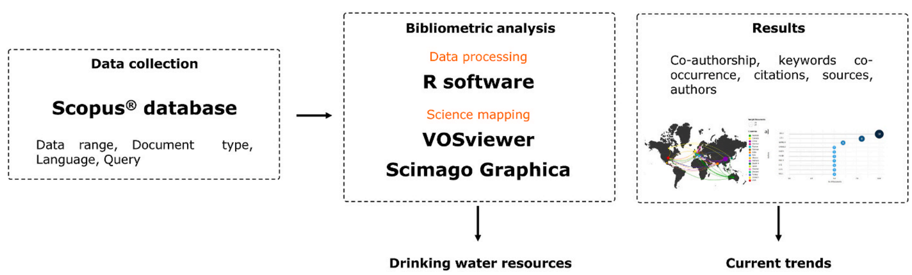
HIGHLIGHTS

- Scientific knowledge on microplastic (MP) pollution in groundwater is reviewed.
- Data collection from Scopus database using a bibliometric approach.
- Groundwater sampling and analysis methods must be implemented and standardized.
- A regulated risk analysis for MPs in drinking water is urgently needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics pollution is little studied in groundwater, compared to other surface water environments. In this review, bibliometric tools were used to determine literature trends and investigate research interests to provide a comprehensive knowledge on this research topic. 215 articles, published between 2009 and 2024, were obtained from the Scopus database, and their bibliometric data were statistically analyzed using the 'bibliometrix' package in R, to determine annual productivity, countries, authors, sources and citations. The co-authorship map and keywords co-occurrence analysis were obtained using VOSviewer and SCImago Graphica interfaces. Samples collection, methods, abundances, and polymers type differed significantly across research. Furthermore, keywords extraction revealed that only a minor fraction (4.6 %) of the total number of articles concerned drinking water sources and ecological risk assessment. This is a critical aspect of this field of research, as the contamination of drinking water sources could lead to the ingestion of microplastics, posing serious risk to biodiversity and human health. Furthermore, the absence of common legislation significantly affects the extent of this contamination. Monitoring studies of MP pollution in groundwater are necessary to develop targeted mitigation strategies to preserve human and environmental health. Finally, the lack of standardized protocols for sampling and analysis methods is a pressing need to encourage further studies on MPs in groundwater and to enable comparison of studies.

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1. Introduction

Groundwater is one of the world's most important natural resources and accounts for about 99% of all liquid freshwater on Earth (UNESCO, 2022). Groundwater not only sustains ecosystems and supports aquatic life, contributing to biodiversity (Hose et al., 2023), but also plays an essential role in both the environment and human health, providing substantial support for the socio-economic and environmental development of society (Campos and Pestana, 2022). Approximately one-third of the world's population directly uses groundwater as a drinking water resource (Li et al., 2021), especially in rural areas where water is not provided by public water infrastructures and in countries where it is the only drinking water resource (Burri et al., 2019; UNESCO, 2022). Where surface water is scarce, groundwater can be an essential means of supply, providing a backup source of clean water for domestic uses such as cooking, drinking and sanitation (Griebler and Avramov, 2015; Tanguy et al., 2023). In addition, groundwater is an extremely important resource for agricultural production, industrial crops and livestock (Moeck et al., 2023).

Considering the increase in population and demand for water by all sectors, dependence on groundwater will only increase in the years to come (UNESCO, 2022). The protection of groundwater and its aquifers should be of paramount importance, especially considering their potential as a drinking-water source (Goldscheider, 2010). However, this precious resource is often understudied and poorly managed. Extreme weather events, such as floods and droughts, are increasingly intensified by climate change, leading to increased variability in precipitation patterns and surface water availability, affecting groundwater abundance and condition (Di Lorenzo et al., 2019; Grönwall and Danert, 2020). Furthermore, the groundwater quality is strongly affected by human activities including urbanization, agriculture, and industry, thereby reducing the suitability of extracted groundwater for human consumption (Nemčić-Jurec et al., 2022). Given the high residence time of groundwater in its host aquifers, pollution of these environments is an almost irreversible process (Lapworth et al., 2021). Many emerging contaminants, such as pesticides, personal care products (PCPs), and perfluorinated chemicals (PFCs), have been reported in groundwater ((Kim D-H et al., 2023; Lapworth et al., 2012; Pradhan et al., 2023). Microplastics (MPs), i.e. plastic particles with dimension between 1 μm and 5 mm (according to ISO/TR 21960:2020), are also among the contaminants found (Viaroli et al., 2022). They are currently one of the most targeted environmental pollutants, and their presence has been documented in almost all environments (Allen et al., 2019; Pinheiro et al., 2023). Scientific and legislative efforts have increased in response to new findings on the global spread of MP pollution due to the exponential growth of plastic production (Plastic Europe, 2024). In 2023, U. S. EPA released the Draft National Strategy to Prevent Plastic Pollution (EPA, 2023) to propose actions to mitigate, reuse, and collect plastic waste and eliminate the discharge of plastic waste from terrestrial sources into the environment by 2040. Among the objectives identified by the Draft, Objective C aims to the increase and coordinate research on micro/nanoplastics in waterways and oceans, with the development of standardized methods for collection, extraction, quantification, and characterization of these particles based on existing methods for both waterways and other environmental compartments. This will be fundamental to protect human health and environmental quality, as several studies have demonstrated the significant negative impacts that MPs can have on organisms and human health (e.g., Bellas et al., 2016; Duncan et al., 2019).

Recent articles highlighted how the gap between surface waters and groundwaters MP research is still wide (e.g., Viaroli et al., 2022). Scientific community has mostly focused on monitoring and assessing their presence in marine and surface waters, neglecting other freshwaters (Mancuso et al., 2023). Historically, plastic pollution research has focused on marine environments, where awareness of plastic pollution initially emerged because of visible accumulations in the oceans and on shorelines (Jambeck et al., 2015; Thompson et al., 2004). These studies then began to raise concerns about ingestion by marine wildlife and the broader ecological impacts of plastic pollution (Wright et al., 2013). To better understand MPs dynamics and the source of input of riverine systems to marine environments, attention over the years has expanded to freshwater bodies, such as rivers and lakes (Baldwin et al., 2016; Derraik, 2002; Dris et al., 2015; Moore et al., 2011). The study of MP pollution in rivers has been crucial, as it has shown that they can act as both sources and pathways for MPs flowing into the oceans (Meijer et al., 2021). As the main link between land and ocean, rivers and other inland waterways transport the majority plastic pollution from land sources to the oceans (Jambeck et al., 2015). The risk to receptors such as groundwater, drinking water supplies, and the subsurface in general has only recently received attention (Geissen et al., 2015; Koelmans et al., 2019; Panno et al., 2019). Groundwater systems have remained largely neglected because of their "invisibility", which contributes to their being perceived as unaffected by the land surface pollution. As the scientific community now recognizes the infiltration potential of MPs in groundwater environments, attention is gradually shifting to groundwater research.

Since groundwater is one of the primary sources of drinking water, it cannot be excluded that its contamination could lead to MP ingestion (Koelmans et al., 2019). The lack of proper regulations means that drinking water treatment plants are often not prepared to handle the presence and remove MPs in the raw water reaching these systems. Moreover, indirect ingestion of MPs can occur through irrigation of agricultural soils with contaminated waters (Wanner, 2021). Among the health risks associated with MPs, there is their potential to act as carriers for other toxic chemicals already present in the aquatic environment, such as bisphenol A (BPA), flame retardants, and heavy metals (Cheng et al., 2023; Kim et al., 2024; Ta and Babel, 2023), by adsorbing them and promoting their transfer and bioaccumulation into organisms. Studies on the toxicity of MPs are still in their infancy, but it has already been shown how their presence in the environment can increase the toxicity of co-occurring contaminants (Sun et al., 2022). In addition, the presence of plasticizers, pigments, or UV stabilizers in the plastics themselves, can pose a health hazard that should not be underestimated (Anbumani and Kakkar, 2018). Thus, it becomes crucial to know the current state of studies regarding MP pollution in groundwater, and the risk it poses to human health.

To deepen knowledge on the global trend and highlight research needs of MP studies in groundwater, bibliometric analysis and science mapping have been combined. Bibliometric analysis is one of the most used tools to identify and assess in detail specific trends in the scientific literature, while science mapping is useful in graphs readability and data visualization. The aims of this review were to: i) provide a comprehensive bibliometric analysis using SCOPUS database, including scientific production, co-authorship, sources, and citations information, and keywords co-occurrence analysis; ii) extrapolate studies that have dealt with groundwater pollution when it is intended for drinking use, to investigate how and whether ecological risk assessment is carried out on MPs, especially when it is water intended for human consumption; iii) highlight the current trends and knowledge gaps existing in studies investigating the presence of MPs in groundwater and the future research needs toward which research could be directed. This comprehensive review contributes to gaining a better understanding of the many issues involving the reality of MPs in groundwater.

2. Methodological approach

Bibliometric analysis is an increasingly popular technique for dissecting and analyzing large amounts of scientific data, allowing mathematical and statistical techniques to be used to process bibliometric data. In this review, bibliometric analysis was applied to the emerging research field of MPs in groundwater. Furthermore, through a meta-analysis on the extracted data, it was possible to extrapolate papers dealing with groundwater as a drinking resource. The next subsections detail the methodology for data collection and processing.

2.1. Literature review and documents extraction

The SCOPUS database (www.scopus.com) was accessed in January 2024, adopting specific search criteria to ensure the quality of the data collected. SCOPUS is one of the biggest sources of bibliographic data produced by Elsevier and is widely used for literature research, providing a comprehensive coverage of scientific production from different study areas (Visser et al., 2021). We established a query to improve the search strategy in the search fields, minimizing the number of uninteresting results as much as possible. Boolean operators, asterisks, and quotation marks were used to optimize the search string, as follows:

("microplastic*" AND "groundwater*") OR ("microplastic*" AND "aquifer*") OR ("plastic polymer*" AND "groundwater*") OR ("plastic polymer*" AND "aquifer*").

The search setting included fields (article title, abstract, keywords), document type (article, review), language (English), publication stage (final), and time span (published from 2000 to present, at the time of writing this paper). The metadata collection methodology was implemented to satisfy the requirements of comprehensiveness and reproducibility by other researchers (Rizzo et al., 2023). The collected information was first processed with mathematical functions implemented in R v.4.3.0 (Foundation for Statistical Computing, 2023), an open-source analysis-oriented program with built-in packages. The package 'bibliometrix' v.4.1.4 was used to collect data from the original documents, and to help show the quality of the uploaded metadata (Aria and Cuccurullo, 2017). A variety of database and file formats are supported by the built-in "biblioshiny" function, which allows graphs and statistics to be obtained quickly and efficiently.

2.2. Science mapping

When conducting a bibliometric analysis, knowledge structure, clustering and coupling analysis are essential. Scientific mapping helps to examine the connections between the various components of studies (Donthu et al., 2021). Co-authorship analysis and co-occurrence network are useful to focus on the social interactions and relationships existing between the thematic cluster of the research field, while showing the corpus of knowledge in the relevant literature (Donthu et al., 2021). For this reason, visualization software can be useful for creating powerful and clear maps. VOSviewer is a free software for mapping and visualizing network data. It effectively organizes data by finding common points between the chosen parameters. Additionally, SCImago Graphica is a recent graphical editor that is particularly effective when used as a complement to VOSviewer.

Keywords are the most reliable indicators to represent the scientific content of an article without examining the entire text, especially the authors' keywords, i.e. those provided by the original authors of the papers (Zhang et al., 2016). To better visualize the structural aspects of scientific research and enable the identification of specific subject areas and trends, clustering analysis can be used. Keywords can be grouped according to their correlation to form thematic clusters and obtain a map of clusters (Xu et al., 2022). VOSviewer v.1.6.20 (www.vosviewer.com, van Eck and Waltman, 2010) was used to extract the authors' keywords from the text. The analysis was set on co-occurrence type, with a minimum keyword occurrence frequency of 2 (out of 672 keywords, 116 met the threshold).

To further deepen the understanding of the global scientific production related to MPs in groundwater, a co-authorship network map was provided. In addition to the most relevant affiliations and authors, the co-authorship network information allows visualizing cooperation between countries and highlighting the countries where the research topic is most relevant. The map was obtained by extracting the original data with VOSviewer, setting countries as the unit of analysis, with a maximum number of countries per document equal to 10, and a minimum number of documents from one country equal to 5 (17 met the threshold). The output was directly transferred to SCImago Graphica *Beta* 1.0.39 (www.graphica.app, Hassan-Montero et al., 2022) for the final visualization. As the correlation maps are often confusing and data-rich, the complementary use of the graphics editor improved graphics and readability.

3. Results and discussion of bibliometric analysis

Although the presence of MPs has been widely documented in almost all aquatic environments, their presence in groundwater has been little investigated for years. The last decade has been crucial for the development of studies on the occurrence, abundance, and transport of MPs in groundwater ecosystems. With only one paper published in 2009, scientific production on this topic has increased exponentially in recent years, as shown in Fig. 1. Although not shown in the graph, 8 studies have already been published between January and February 2024. However, the number of studies on MPs in groundwater is not even comparable to those on surface aquatic resources (Santini et al., 2022; Tang et al., 2023). The hidden nature of groundwater reserves, combined with often limited accessibility, makes it challenging to assess the consequences of MP contamination in these environments (Campos and Pestana, 2022).

A total of 215 studies were included in the bibliometric analysis (Table 1). Although the selected time frame began in 2000, the actual time span was dictated by the SCOPUS database, as the first paper of interest was published in 2009. Articles are the most prevalent document type, with a total of 171, followed by reviews, accounting for 44, from 82 different sources. Additional information on the annual growth rate, authors, and contents of the documents are reported in Table 1.

3.1. Statistical analysis

Whereas the investigation of MPs in groundwater is a topic of emerging interest, bibliometric analysis yielded articles from 64 different countries from five continents (Africa, America, Asia, Europe, and Oceania). The largest contribution came from China (n = 69), followed by the USA and Germany (both n = 27), India (n = 23), and the United Kingdom (n = 23). The 17 countries that contributed most to the research field are shown in Fig. 2a, along with the collaboration links

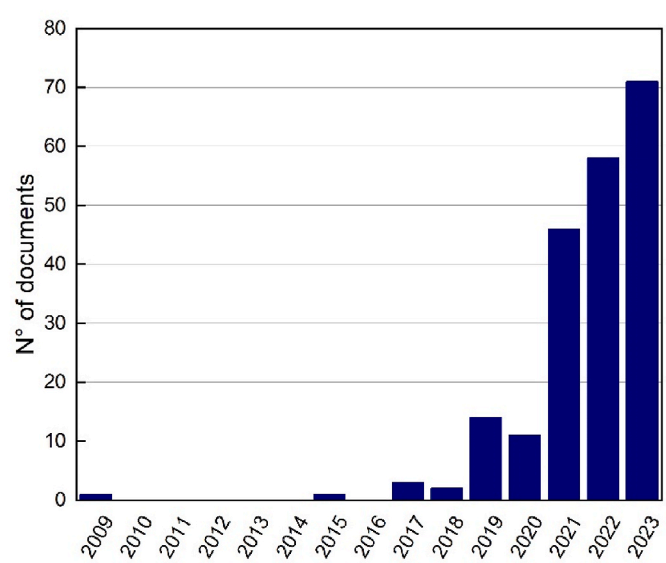

Fig. 1. Number of publications per year studying MPs in underground aquatic environments from January 2009 to December 2023. Source: SCOPUS.

Table 1
Some of the main information obtained with "biblioshiny".

Main information about data	
Timespan	2009:2024
Sources (Journals, Books, etc.)	82
Documents	215
Annual Growth Rate (%)	14.87
Document Average Age	2.31
Average citations per documents	56.99
Document Types	
Articles	171
Reviews	44
Authors	
Authors	1084
Authors of single-authored documents	3
Single-authored documents	3
Co-Authors per documents	6
International co-authorships (%)	34.88
Document contents	
Keywords Plus (ID)	2570
Author's Keywords (DE)	672

between them. The results show that China is the country with the largest commitment to research collaborations, followed by the USA, the UK and Germany. In addition, Fig. 2b shows the 10 most influent countries in terms of corresponding author, and for each country the number of articles with co-authors from the same country and the number of articles with co-authors from different countries.

However, in some countries there is still no evidence of studies related to MPs monitoring in groundwater. In addition, the predominance of some countries limited in terms of scientific production and collaborations shows a strong lack of homogeneity in research. Especially in some developing countries, where plastic pollution represents a serious environmental concern, the lack of data on the qualitative status of groundwater could be detrimental to human health. The expansion of collaborative networks is key to pooling scientific knowledge on MP pollution in a sensitive environment such as groundwater.

The most relevant authors, most cited documents and most relevant sources are other significant data that can be extrapolated from the bibliometric analysis. This information can guide other authors in performing further research in the still underdeveloped field of groundwater contamination and set up novel collaborations between different institutions. Among the top 10 most relevant affiliations, listed by the number of articles (Figs. S1 and SI), KANGWON NATIONAL UNIVERSITY in South Korea emerges as the most productive (n = 37), followed by JINAN UNIVERSITY in China (n = 36) and UNIVERISITY OF BAYREUTH in Germany in third place (n = 24). However, it can be seen that Chinese universities are generally the most prolific, in line with the fact that China is the largest contributor to scientific production in this field. Fig. 3a shows the top 10 most relevant authors. Based on their scientific productivity, WU J has the higher number of published papers (10), followed by LEE J-Y (8) and WANG H (6), while the remaining all have 5 publications. The productivity of the same authors can also be visualized by progress over time (Figs. S2 and SI), considering their annual production on this topic. LEE J-Y is the author with the longest period of production, having authored and co-authored many reviews and comments on this topic (e.g., Cha et al., 2023; Jeong et al., 2023; Lee et al., 2022).

Based on data provided by 'bibliometrix', the number of citations of an article can be calculated as global or local. Global citations refer to the number of citations a document receives from the entire bibliographic database (i.e., SCOPUS), while local citations correspond to the impact of a paper only on the documents included in the collected and processed data (such as the 215 documents of this review) (Aria and Cuccurullo, 2017). The top 10 most global cited documents are illustrated in Fig. 3b, while the top 10 most local cited documents are presented in Fig. 3c. The two graphs show apparently inconsistent results, as a portion of the global citations may come from disciplines other than the research area of interest (Aria and Cuccurullo, 2017). Despite not directly addressing MPs, Teuten et al. (2009) present the highest number of global citations (citations number = 1955), in line with the fact that the potential of plastic chemicals to reach the groundwater was raised for the first time. The review of Koelmans et al. (2019) about microplastics in freshwaters and drinking water (including groundwater, tap and bottled water) is the second most globally cited (citations number = 1217) probably due to the fact that it is the first article to address the need to sample large volumes (at least 1000 L) when studying drinking water sources, considering the possible rarefaction of MPs concentration in this type of matrix. The top two documents most local cited include Mintenig et al. (2019) and Panno et al. (2019), as they provided experimental data on the presence of MPs in some of the most relevant underground aquatic sites, drinking water sources and karst groundwater system, respectively.

Among the 82 sources (journal, books, etc.) identified through the bibliometric analysis, the top 10 are shown in Fig. 3d, sorted by number of papers. SCIENCE OF THE TOTAL ENVIRONMENT is the most significant journal concerning the field of MPs in groundwater, with 16.3% of published articles, followed by WATER RESEARCH, with 8.8%, and ENVIRONMENTAL POLLUTION, with 6%.

The results of the keywords extraction from studies on MPs in groundwaters and their correlation is shown in Fig. 4. The relatedness between MPs and their potential sources, transport, varieties, and hazardous effects can be analyzed by the co-occurrence network. In addition to the terms already combined in the search strings, some of the most frequent keywords were 'transport', 'nanoplastics', 'pollution', 'soil' and 'surface water' (Table S1, SI).

Three color-coded clusters were generated, each comprising words that have a similar meaning or that occur frequently together. Each cluster can be attributed to a research area concerning a particular aspect of the investigation of MPs in groundwater environments. The red cluster is the largest (n = 59) and mainly includes terms related to the correlation between groundwater and terrestrial pollution. In detail, 'agriculture', 'soils', and 'mulch film' indicate the frequency with which groundwater pollution is examined in relation to agricultural soils. Through vertical migration, mulch films, fertilizers and pesticides can lead to groundwater contamination, as well as being harmful to the soil itself (Wanner, 2021). The green cluster (n = 36) is more related to the mechanism of transport, retention, and fate of MPs in the different porous media typically found in aquifers (e.g., karst, vadose zone). Lastly, the blue cluster (n = 21) represents information on the risks and possible toxicological effects of MPs in groundwater, especially when related to drinking water. Some of the most frequently recurring words are 'human health','drinking water', and 'bioaccumulation'. Moreover, 'pharmaceuticals' and 'heavy metals' suggest the presence of correlation studies between MPs and other environmental contaminants (Selvam et al., 2021). The keyword analysis shows that the scientific community is currently focused on studying the transport processes and pathways of MPs from surface environments.

4. Advancements in groundwater microplastic research

The bibliometric results demonstrate how the investigation of MPs in groundwater is still in its early stages. Based on the results of the aforementioned analysis, this paragraph provides an overview of some key aspects involved in the monitoring of MPs in groundwater, specifically considering sampling, detection, abundances and compositions, as well as potential sources of contamination (see Table 2).

4.1. *Sampling and study area*

The identification and characterization of MPs in environmental matrices is challenging due to their wide variety of physicochemical characteristics (Lusher et al., 2020). The feasibility of collecting representative samples is not trivial and water sampling techniques still

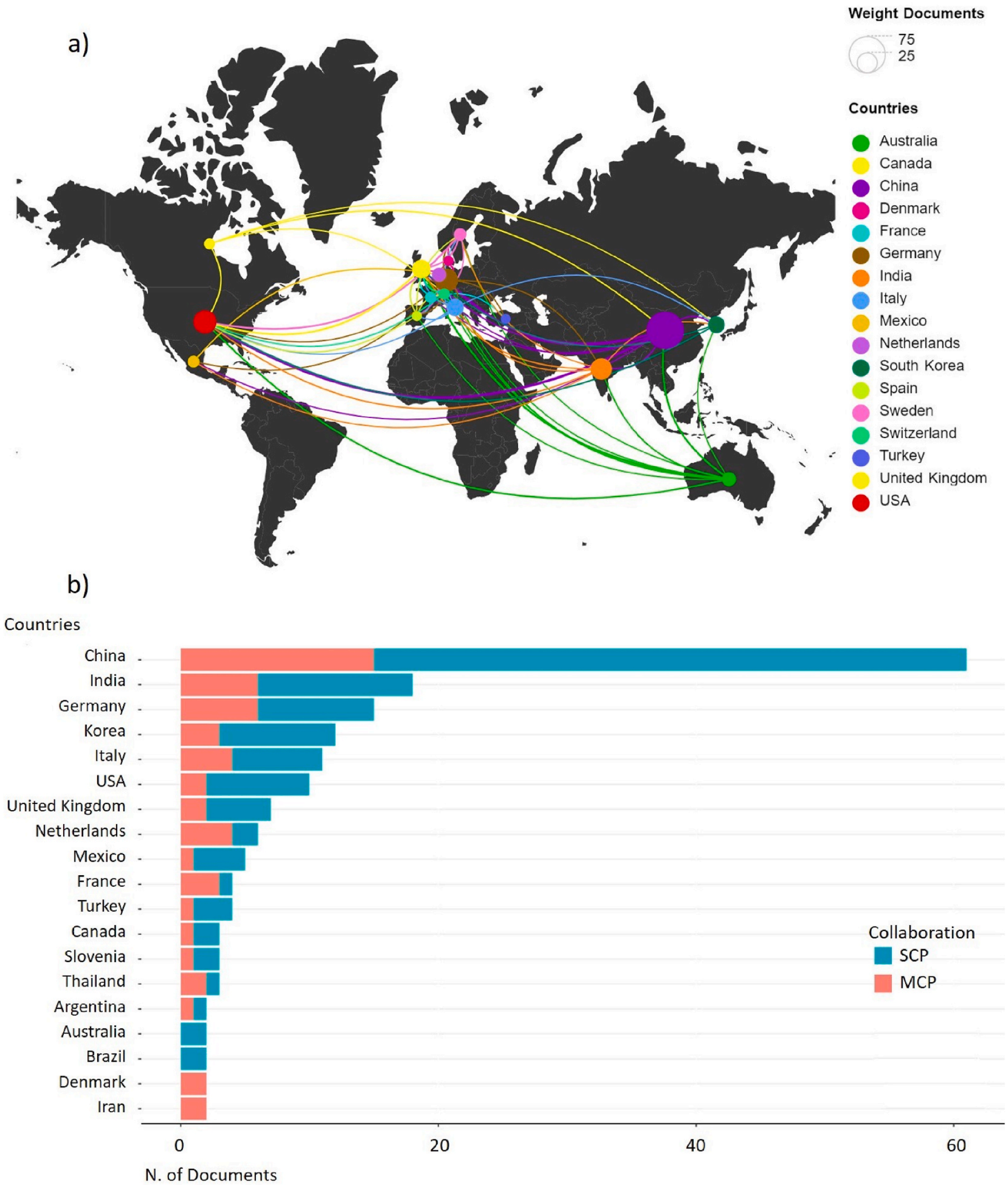

Fig. 2. (a) World map showing the network of co-authorship among countries. The size of the disk marks is indicative of the number of published articles from each country, while the connecting lines indicate cooperative relationships. The colors of the lines correspond to those of the country from which the collaboration starts (created with VOSviewer and SCImago Graphica). (b) Number of articles in relation to the corresponding author's country. The number of articles published in collaboration with other countries is also shown. SCP: single country publication, MCP: multiple country publication (source: 'bibliometrix').

mainly focus on surface waters (GESAMP, 2019; Gago et al., 2019). The most common methods for collecting floating marine MPs are described in the "GUIDELINES FOR THE MONITORING AND ASSESSMENT OF PLASTIC LITTER IN THE OCEAN", published by GESAMP (2019). These techniques include surface net tow, such as Neuston net, Manta trawl, Mega trawl, or Bongo net, typically used for deeper water sampling. Bulk water sampling can also be used to collect a few to more than 100 L from the water surface or subsurface, using a container or a submersible pump. Afterwards, this water is usually filtered on filter paper, mesh, or sieve. In addition, among the goals of the JPI-Oceans BASEMAN project (Gago et al., 2019) is to develop reliable techniques for sampling seawater (both water column and sea surface), essential for an accurate identification and quantification of MPs. Here, the use Manta trawl and the Neuston net is generally recommended, while Niskin bottles are a popular technique for collecting water from various depths in a water column.

However, none of these methods is completely feasible for MP sampling in groundwater. Currently, there are no internationally established sampling methods and detection techniques for MP, especially in groundwater. Some efforts have only recently been made (e.g., Chia et al., 2022; Lee et al., 2022), while with regard to water for human consumption, the European Union has recently developed a major Directive on its quality (EU Directive, 2020/2184), followed by Decision (2024)/144/EU, requiring the inclusion of MPs in the "checklist" and the harmonization of methods for their quantification. However, these guidelines currently exclude specific requirements for monitoring of primary sources of MP at direct supply points, such as springs and wells. Developments in drinking water regulations could serve as a framework for future groundwater monitoring laws.

A minimum sample volume above 500 L has been suggested for

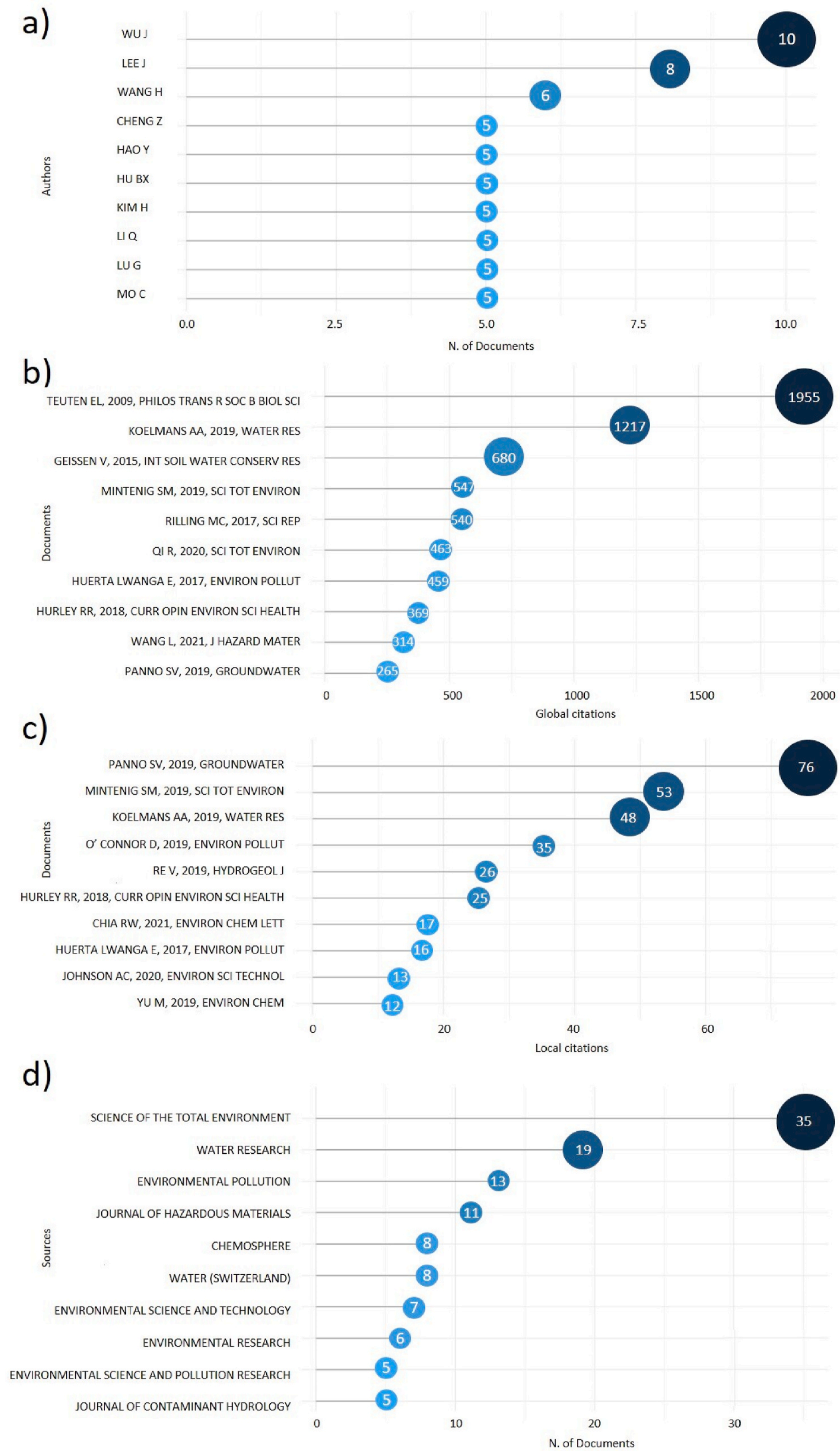

Fig. 3. (a) Top 10 of the most relevant authors by number of documents. (b) Top 10 of the most global cited documents. (c) Top 10 of the most local cited documents. (d) Top 10 of the most relevant sources by number of documents (source: 'bibliometrics').

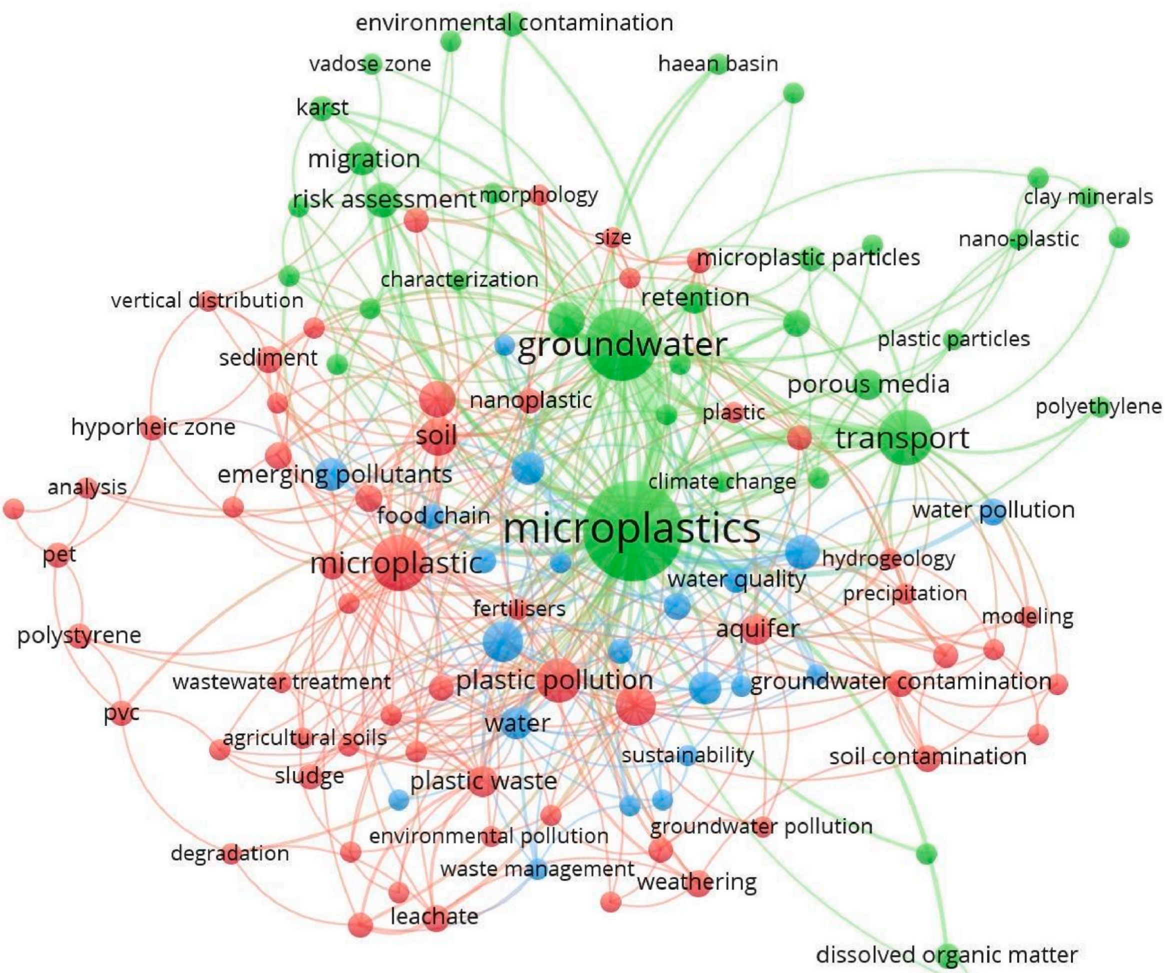

Fig. 4. Co-occurrence map of authors' keywords in studies on MPs in groundwater. Node and word sizes are related to the frequency of occurrence of the 116 keywords extracted from the 215 documents. The relatedness of the items (i.e., keywords) is determined by the number of documents in which they occur together; each color represents a cluster (generated by VOSviewer).

remote locations such as groundwaters (Koelmans et al., 2019), where the expected MP concentration is very low or may be very rarefied. Despite the lack of standardization for sampling procedures, two main methods are generally adopted for groundwater sampling: the bulk method and reduced volume sampling (Hidalgo-Ruz et al., 2012). The first involves collecting a few liters or fractions, while the second allows larger volumes to be filtered directly *in situ*, usually through stainless-steel cartridge filters or stainless-steel sieves (e.g., Cha et al., 2023; Nesterovschi et al., 2023). In addition, hydrogeological properties, such as depth and flow rate, and the geological media, inevitably affect the efficiency and reliability of sampling procedures (Lee et al., 2022).

When investigating groundwater, it is necessary to provide a careful description of the surrounding area, e.g., proximity to industries, farms, or landfills, as the land use may influence the type of MPs present, allowing a more precise individuation of the release (Samandra et al., 2022). The close synergy between the surface environment and groundwater means that the number of interactions between these two spheres can be extremely high. Atmospheric depositions, urban infrastructure, and agricultural activities represent only some of the possible sources of MPs in groundwater (Moeck et al., 2023; Viaroli et al., 2022). Soil infiltrations and proximity to landfills can also act as point sources of MP pollution, for instance due to percolation of laden leachate (Singh and Bhagwat, 2022). In some cases, plastics used in tanks, fittings, and pipes can contribute to MPs release into drinking water sources (Mintenig et al., 2019; Weisser et al., 2021), although it is not always easy to attribute their certain origin.

Understanding the role of sediments in MP pollution is equally important because they influence the distribution, transport, and sampling of MPs in groundwater systems. Sediments can act as a medium for MP transport, resuspension, and deposition in groundwater systems, and their grain size can influence MP distribution (Waldschläger et al., 2022). In particular, Enders et al. (2019) linked the presence of MPs to finer particle size fractions of sediments, suggesting that analogous mechanisms regulate their distribution. Despite the natural process, human activities such as drilling, pumping or agricultural activities, can remobilize previously deposited microplastics, allowing them to re-enter the groundwater stream. For this reason, the sampling method chosen must be taken into account when concerning groundwater, otherwise MP abundance will not be representative of the water sample alone. The relationship between sediment characteristics, MP size, and resuspension behavior is critical to understanding how MPs migrate through aquifers and affect groundwater quality.

Among the types of aquifers investigated, karst ones play a key role, as they constitute about a quarter of the world's drinking water sources (White, 1988). Due to their open nature, they are susceptible to the rapid transfer of contaminants from the surface, which can enter karst systems directly through caves or be transported through rock fractures (White, 1988). In the case of manmade interventions, such as for wells and boreholes (Samandra et al., 2022; Shi et al., 2022), information on the diameter, depth, presence or absence of capping, as well as a description of the casing materials should be provided (Lee et al., 2022).

Table 2
Studies monitoring MPs in groundwater.

Reference	Sampling				Analysis		Microplastics		Source of contamination
	Country	Aquifer type	Sampling	Volume	Sample treatment	Detection techniques	Abundance[a]	Polymer type	
Balestra et al. (2023)	Italy	Cave waters	Glass vessels	1 L	Oxidative treatment	• Microscope with/ without UV light • μFTIR	28 items/L	PE > 50%	Synthetic clothes, electric system works, tourism, shallow pollution
Baraza and Hasenmueller (2023)	USA	Springs	Amber glass bottles and PP bottles	1L	/	• Stereomicroscope • FTIR	9.2 to 81.3 items/L	Cellulose >70%	Land surface
Cha et al. (2023)	Korea	Wells	Stainless-steel filter cartridge	500 L	• Oxidative treatment • Density separation	μFTIR	0.02–3.48 items/L	PE, PP > 40%	Any definite source of pollution
Kim Y. I. et al. (2023)	Korea	Wells and springs	Stainless-steel mesh filters	500 L	• Oxidative treatment • Density separation	μFTIR	0.07 items/L	PP > 50%	Agricultural area
Nesterovschi et al. (2023)	Romania	Spring	Stainless-steel sieves	500–1000 L	Wet peroxide treatment	μRaman	0.034 and 0.06 items/L in the two sites	PET, PP	Rural households, garbage dump
Panno et al. (2019)	USA	Wells and spring	HDPE bottle	2 L	/	• Microscope • Pyr/GC-MS	6.4 items/L	PE	Littering, drainage of effluent from septic systems
Samandra et al. (2022)	Australia	Monitoring bores	Amber glass bottles	1 L	• Oxidative treatment • Density separation	LDIR	38 ± 8 microplastics/L	PE, PVC >50%	Agricultural fields, domestic cleaning products, clothing, residential area
Shi et al. (2022)	China	Monitoring well	Brown glass bottles	1 L	Oxidative treatment	• Optical microscope • μFTIR	29 items/L	PA, PE, PP, PVC, PS	Sewage treatment plant, landfill, vegetable production
Alvarado-Zambrano et al. (2023)	Mexico	Borehole	PVC bailer sampler and amber glass bottles	1 L	• Oxidative treatment • Density separation	• Stereomicroscope • FTIR-ATR	18.3 items/L	iPP, HEC >30%	Agricultural materials

[a] Abundances are reported as mean values or ranges as indicated in the corresponding articles.[FTIR]: Fourier Transformed Infrared spectroscopy, [SEM]: scanning electron microscopy, [EDX]: energy dispersive X-ray, [Py-GC/MS]: pyrolysis gas-chromatography coupled with mass-spectrometry, [LDIR]: laser direct infrared spectroscopy, [ATR]: attenuated total reflection, [PE]: polyethylene, [PP]: polypropylene, [PET]: polyethylene terephthalate, [PVC]: polyvinyl chloride, [PA]: polyamide (nylon), [PS]: polystyrene, [iPP]: isotactic polypropylene, [HEC]: hydroxyethyl cellulose.

4.2. Sample treatments and analysis

Discrepancies in extraction and detection methods lead to significant inconsistencies between the results of different studies. The final results are significantly affected by the sampling protocol and sample pre-treatment/extraction. Owning to the lack of standardized procedures, a wide variety of approaches can be used to process the samples, involving various chemical reagents (enzymes, acids, alkalis, oxidants), saturated salt solutions with different density and filters with diverse pore sizes and materials (Zhu and Wang, 2020).

Accurate identification of MPs in groundwater is essential for a comprehensive understanding of their fate and transport and is a key information for assessing the associated ecological risk (Pan et al., 2021). The most used method for chemical characterization is vibrational spectroscopy, i.e., FTIR and Raman, often coupled with preliminary visual inspection (e.g., Kim Y. I. et al., 2023; Shi et al., 2022). Other characterization approaches could be thermal analysis techniques, such as pyrolysis coupled with gas chromatography-mass spectrometry (Pyr/GC-MS) (Panno et al., 2019). However, these methodological differences can lead to inconsistent MP detection rates between studies, even when investigating the same environment.

Moreover, the large number of processing the samples may undergo enhances the possibility of underestimating the real concentration of MPs, especially for low level of abundances as the ones usually detected in groundwaters. Thus, to estimate the recovery rates it could be useful to perform positive controls using spiked MPs (Brander et al., 2020), although it is still not a common procedure and only a few implements it (e.g., Esfandiari et al., 2022; Samandra et al., 2022).

4.3. Abundances and classification

The abundances and classifications of MPs in groundwater are influenced by various factors. Regional land use, proximity to industrial areas and agricultural activities undoubtedly influence pollutant concentration levels. Recent studies have reported varying concentrations of MPs in groundwater, ranging from negligible levels, such as 0.00011 items/L in raw water from WTWs in the UK (Johnson et al., 2020), up to 2103 items/L in monitoring wells in China (Mu et al., 2022). Groundwater near populated areas or affected by increased agricultural runoff tends to have higher MP concentrations than, for example, springs located at higher altitudes where human activities are less present. Nesterovschi et al. (2023) found abundances of 0.034 items/L and 0.06 items/L in two Romanian karst springs, where rural households were imputed as a possible source of contamination. Comparable results were obtained by Kim Y. I. et al. (2023), in which Korean wells and springs found abundances between 0.006 and 0.192 particles/L. Cha et al.

(2023) also reported abundances ranging from 0.20 to 3.48 particles/L in wells in a Korean agricultural area, ignoring a specific source of pollution. In contrast, higher abundances have been found, for example, by Panno et al. (2019), who investigated U.S. karst springs, finding up to 15 items/L, where more relevant source of contamination, such as drainage of effluent from septic systems, were identified, and Balestra et al. (2023) in an Italian touristic cave with up to 28 items/L. When examining monitoring bores and wells, which are often located near agricultural areas, concentration is comparable even among studies from different countries. Indeed, it is noted that Samandra et al. (2022) in Australia, Shi et al. (2022) in China, and Alvarado-Zambrano et al. (2023) in Mexico, found concentration of 38 (±8), 29, and 18.3 items/L, respectively. However, MP concentrations observed in groundwater are significantly lower than those documented in surface water, up to 809, 000 items/m^3 as stated in Nunes et al. (2023). This stark contrast highlights the different dynamics and factors influencing MP distribution in groundwater and surface water. Surface waters, with their direct connection to different pollution sources, tend to accumulate higher concentrations of MPs. In contrast, groundwater, being shielded by geological layers and often characterized by lower flow velocities, appears to have lower MP concentrations (Nesterovschi et al., 2023). Baraza and Hasenmueller (2023) show that floods, i.e., high flow events, increase the concentration and the size of MPs in cave waters compare to baseflow conditions (81.3 vs 9.2 items/L), maybe enhancing their mobilization from surface recharge or sediment resuspension within the cave. The protective nature of aquifers, combined with the filtration processes that occur during the percolation of water in the subsurface water, may contribute to the lower presence of MPs in groundwater compared to surface water, but also to a residence time of these pollutants much higher compared to that in surface waters, as suggested by Esfandiari et al. (2022), who found abundances of 0.1–1.3 MP/L in an Iranian alluvial aquifer, assuming a possible residence time ranging from years to decades.

The impact of land use in the surface environment plays a crucial role in the release of MPs into groundwater, as highlighted by Sangkham et al. (2023). This feature affects the type of polymers detected. Since the chemical speciation of polymers is wide, it is difficult to find a trend pattern when assessing their contamination. For example, Samandra et al. (2022) correlated the presence of PE, PP, PVC, and PET in groundwater bores with the proximity of a meat processor plant, while Balestra et al. (2023) associated the abundance of PE, PVA, and other polymers in an Italian karst cave to tourism and works on the cave's electrical systems. Despite these heterogeneities, the most abundant polymers result in polyethylene (PE) and polypropylene (PP), which are widely used plastic polymers (Plastic Europe, 2024), as shown in Table 2.

More attention should also be paid to the size of MPs, as this type of classification allows better assessment of the risk of ingestion by organisms, particularly groundwater communities. Particle ingestion rates are strongly dependent on size, as smaller MPs are more bioavailable and increase the risk of entering the food chain. Groundwater communities are sensitive and poorly resilient, so they are easily affected by degradation of their habitat (Haegerbaeumer et al., 2019). The interaction between MPs and living organisms can lead to bioaccumulation, contributing to the spread of MPs through biota, potentially disrupting ecosystems and impacting water quality. Consequently, understanding the sizes is essential to predict the overall impact of MPs in groundwater environments.

Despite the inconsistency due to the lack of common monitoring guidelines, early evidence of MP presence in underground reservoirs remains a warning sign, especially when contaminated sites are intended for drinking purposes.

5. Importance of risk assessment for drinking water resources

The assessment of the ecological risk associated with MPs in groundwater, particularly as a drinking water resource, is a pressing need, given the scarcity of data on their potential toxic effects. The toxicity of MPs is still a topic of debate. Some studies have been done to assess human exposure to MPs, through in vitro and in vivo experiments (Liu and You, 2023). It has been shown that MPs can affect organisms in different ways by inducing inflammatory reactions (Liu et al., 2020), neurotoxicity and cytotoxicity effects (Deng et al., 2017; Hwang et al., 2019), and affecting reproductive growth (Schür et al., 2020). Moreover, the presence of additivities and plasticizers in polymers could represent only the "tip of the iceberg". A relatively unexplored field is the study of the synergistic interaction of MPs and other organic contaminants, as stated by (Sun et al., 2022), who showed that MPs increase the bioaccumulation of co-contaminants and worsen their toxicity, thus defining a "synergistic health hazard". This also implies that when it comes to toxicity data, considering only MPs could lead to an underestimation of the real health risk of MPs. In addition, particles size, exposure time and concentration are determinants of the intrinsic toxicity. It should also be considered that toxicological studies are often conducted in controlled laboratory settings that do not accurately reflect the complex conditions of natural environments, thus making toxicity test results limited and unrealistic (Sun et al., 2022).

Despite its recognized importance, the absence of a universally accepted and standardized MP risk assessment model poses a significant obstacle. Although some potential approaches have been applied by researchers such as Castillo et al. (2024) and Pan et al. (2021), their methodologies are not yet widely adopted or endorsed by regulatory agencies. These models typically involve the calculation of various indices, including the MP concentration factor (CFi), ecological risk factor (Ei), and potential ecological risk (RI), for the different types of polymers detected in the samples. Additionally, hazard scores (H) are derived based on the percentages of polymer types (Pn) and assigned polymer scores assigned to each according to the criteria proposed by Lithner et al. (2011). The practical application of these methodologies depends on the availability of comprehensive data on background values, MP concentration, and composition, which are often limited, especially for drinking water sources. The dependence on actual polymer concentrations in the model followed by Castillo et al. (2024) and Pan et al. (2021) is particularly relevant. In fact, the CFi is directly proportional to the concentration level, and so are the PLI_i, E_i and RI factors, which are calculated through CFi. Therefore, it is reasonable to assume that a realistic health risk is attributable to higher MP concentrations, depending on the sources, the surrounding environment and proper assessment of pollution levels (Yuan et al., 2022).

Articles related to drinking water and health risks were extracted by keyword analysis to further examine the bibliometric data. The procedure is presented in the SI (S1 and Table S2). Among the 215 documents selected, only 4.6% are closely related to drinking water sources and health risks, and fewer of these provide all the information necessary to conduct an in-depth risk analysis (Table 3). Only 2 of the 10 papers concerning groundwater for drinking purposes already present a risk assessment calculation related to MP pollution. Altunışık (2023) evaluated the microplastic contamination factors (MPCF) and pollution load index (MPLI) in bottled water based on previous studies by Enyoh et al. (2021), Ibeto et al. (2023), and Kabir et al. (2021). The author reported a classification of the investigated samples as follows: 12% of all samples had low contamination, 40% had moderate contamination, 28% had important contamination, and the remaining 20% had high contamination. An additional calculation was conducted to assess the estimated daily intake (EDI) of MP concentrations in bottled water. Despite the calculated low level of exposition through the consumption of natural and mineral waters from the various brands investigated, a long-term intake of MP-contaminated bottled water may still pose a significant risk to human health. Despite not being included in this analysis as it deals with coastal groundwaters not intended for human consumption, Valsan et al. (2023) was the only to apply an ecological risk assessment following the approach previously proposed by Lithner

Table 3
Overview of the data provided by the selected articles (n = 10), required for conducting a risk analysis.

Reference	Sample type	Ecological risk assessment	Chemical characterization	Concentration of each polymer	Polymers %	Background values[a]
Mintenig et al. (2019)	Water from different points of drinking water supply system	✘	✔	Extractable from the graph	Extractable from the graph	✘
Paredes et al. (2019)	Water from water supply system (sources, reserves, distribution networks and hydrants)	✘	✘	✘	✘	✘
Almaiman et al. (2021)	Bottled and tap water	✘	✔	Not available for all the identified polymers	Not available for all the identified polymers	✘
Pittroff et al. (2021)	Processed drinking water and tap water	✘	✔	Extractable from the graph	✔	✔
Bäuerlein et al. (2022)	Water from water supply system	✘	✔	✔ (but difficult to extract from the graph)	✔ (but difficult to extract from the graph)	✘
Shi et al. (2022)	Groundwater from a drinking-water source area	✘	✔	✘	✘	✘
Altunışık (2023)	Bottled water	✔	✔	✘	Average values	✘
Maurizi et al. (2023a)	Water from water supply system	✘	✔	✔ (but difficult to extract from the graph)	✔ (but difficult to extract from the graph)	✘
Maurizi et al. (2023b)	Water from drinking water treatment plant	✘	✔	✔ (but difficult to extract from the graph)	✔ (but difficult to extract from the graph)	✘
la Cecilia et al., (2024)	Water from different points of drinking water supply system	✘	✔	✔ (but difficult to extract from the graph)	✔ (but difficult to extract from the graph)	✘

[a] Background values were given for natural particles, without further definition, although the risk analysis should be based on background values related to microplastics.

et al. (2011), showing Polymer Risk Hazard and Potential Ecological Risk Index values falling in the highest risk category level for the analyzed samples, mainly due to the significant presence of polyester, a polymer with a high hazard score.

As shown in Table 3, except Paredes et al. (2019), all the other selected articles do not provide a specific risk assessment associated with MPs, but they include the chemical characterization of the polymers, a fundamental information for a potential subsequent calculation. Therefore, despite the concentration of each polymer class and the respective percentage detected in the drinking water samples were detailed in the manuscript only by Pittroff et al. (2021), in all the other cases they have been graphically represented. The extraction of this information from the graphs could be complicated, but in case of need for risk assessment calculation may be provided by the original authors. On the other end, the most common gap regards the background values, which are not available for any of the target studies. Despite Pittroff et al. (2021) indeed reporting a background value of the study, this refers to natural particles only, although the risk analysis should be based on synthetic polymer background concentrations. The limited availability of background information for most sites further hinders a comprehensive assessment of MP contamination in drinking water sources. Factors such as land use patterns, anthropogenic activities, and environmental conditions play crucial roles in influencing MP transport and fate in groundwater, however these data are frequently missing or incomplete in existing studies. In addition, the inconsistency of intrinsic toxicological data associated with MPs hinders the ability to implement a comprehensive risk analysis, and the current toxicological literature specific to groundwater systems remains limited, creating significant knowledge gaps. Addressing these knowledge gaps and developing standardized risk assessment frameworks are critical for advancing our understanding of MP-associated ecological risks in groundwater and informing effective mitigation strategies to safeguard public health and environmental quality.

6. Identifying research needs

As previously discussed, studies on the presence of MP in groundwater have only recently received increasing attention. However, several critical knowledge gaps still persist regarding the peculiarities of these pollutants and the environments in which they have studied. The next section focuses on some of these issues, which deserve further investigation and research attention.

First, standardized protocols or guidelines for sample collection, pretreatment methods, and analysis specifically developed to address MPs in groundwater are lacking. Groundwater is a sensitive environment, and common sampling techniques may not be suitable. Limited accessibility, such as for caves or high-altitude springs, makes it difficult to carry bulky equipment, and often only a few liters of water can be collected for analysis (Balestra et al., 2023; Shu et al., 2023). Moreover, the dearth of analysis protocols affects data reliability, hampers comparability across studies and regions, and reduces the accurate understanding of the global status of groundwater quality. In addition, when dealing with MPs pollution, contamination control should be mandatory, so that the true abundance is not under- or overestimated (Jeong et al., 2023).

Due to the importance of groundwater in the hydrological cycle, knowledge of the hydrological characteristics and properties of the study area is essential (Lee et al., 2022), as contaminant loading depends on the local hydrogeological setting as well as the recharge rate (Viaroli et al., 2022). The close synergy between the surface environment and groundwater implies that the number of interactions between these two environments are extremely high. Information such as lithology, hydraulic conductivity, recharge condition, and flow direction can influence the distribution of MPs and allow estimation of aquifers' susceptibility to this class of contaminants (Re, 2019). Currently, few field- and laboratory-scale studies on the process of MPs entry into groundwater and its link to hydrogeological properties (e.g., Okutan et al., 2022; Park et al., 2023). Understanding how MPs migrate through geologic media is pivotal to accurately assess their environmental impact (Chia et al., 2021), as well as their distribution and residence time (Goeppert and Goldscheider, 2021), and the potential impact on soil quality and properties.

The potential long-term effects of MP contamination of groundwater quality and ecosystems' health are still poorly understood (Hose et al., 2023). The study of bioaccumulation pathways, toxicity, and ecological consequences of MPs in groundwater is essential to assess health implications on humans and underground life. In addition, MPs can adsorb other contaminants concurrently present in these environments, such as PAHs and antibiotics (Ding et al., 2023; Li et al., 2023). Therefore, the risk of exposure through direct ingestion by fauna and through drinking water sources for humans could be underestimated. MP pollution of groundwater and aquifers should be given more attention, considering the still unclear effects on human exposure to this contaminant. Moreover, the lack of a chemical risk assessment in a regulatory context and suitable toxicological studies means that when they are intended for human consumption, these resources are not adequately monitored for this contaminant (Koelmans et al., 2019; Sun et al., 2022).

7. Conclusions

In this paper, a bibliometric review on the occurrence of MPs in groundwater is presented. From the analysis of the bibliometric data, including the most relevant countries, authors, sources, and keywords co-occurrence analysis, it can be concluded that data on MP contamination in groundwater are still limited. Despite advances in sampling methods, analytical techniques, and classification methodologies, critical issues and knowledge gaps persist, including the lack of standardized methodologies, which hinders data comparability, and limited understanding of transport mechanisms and long-term impacts of MPs on groundwater systems. Furthermore, the prioritization of studies focusing on drinking water sources is of paramount importance, and the integration of MP-adapted ecological risk assessments will facilitate the preservation of groundwater quality and ecosystem integrity in the face of increasing MP pollution. A comprehensive understanding of the extent and implications of MP contamination in groundwater is essential to safeguard human health and ensure the security of water resources. Future research should focus on interdisciplinary collaborations and address the gaps identified in this review to advance our understanding of MP pollution in groundwater environments.

CRediT authorship contribution statement

Laura Sforzi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Sarti:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Saul Santini:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Tania Martellini:** Writing – review & editing, Writing – original draft, Supervision, Data curation. **Alessandra Cincinelli:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2024.101375.

Data availability

Data will be made available on request.

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