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REVIEW ARTICLE

Global hotspots and trends in interactions of microplastics and heavy metals: a bibliometric analysis and literature review

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Abstract
Microplastics (MPs) are identified as emerging contaminants; however, their interactions with heavy metals in the environment have not been well elucidated. Here, the research progress, hotspots, and trends in the interactions of MPs and heavy metals were analyzed at a global scale using a bibliometric analysis combined with a literature review. We comprehensively searched the Web of Science Core Collection database from 2008 to July 5, 2022. A total of 552 articles published in 124 journals were selected, which came from 70 countries and 841 institutions. The most contributing journals, countries, institutions, and authors were identified. Visualization methods were used to identify high co-citation references and hot keywords in the 552 articles. Evolutionary and cluster analyses of hot keywords suggested several research hotspots in the co-contamination of MPs and heavy metals, including their toxicity and bioaccumulation, the adsorption and desorption behaviors, the environmental pollution and risk assessment, and their detection and characterization. Based on the current research status, several directions of priority are recommended to understand the interactions between MPs and heavy metals and their potential risks. This article can help recognize the current research status and future directions in this field.

Keywords Microplastics · Nanoplastics · Heavy metals · Bibliometric analysis · CiteSpace · Toxicity

Introduction

Increasing evidence confirms that microplastics (MPs) distribute in nearly every ecosystem on the planet, including marine and freshwater environments, soil, atmosphere, and even Arctic areas (Murphy et al. 2016; Auta et al. 2017; Morgana et al. 2018; Chen et al. 2020; Wang et al. 2022c). One estimation shows that the global release of primary MPs from commercial and household activities into the environment is in the order of 3.2 million tons/year (Boucher and Friot 2017). Another estimation shows that up to 430,000 and 300,000 tons MPs per year release into European and North American farmlands, respectively (Nizzetto et al. 2016). MPs can cause various negative impacts on environments and the organisms therein. After ingestion by organisms, MPs can accumulate in their digestive tract (Ma et al. 2020; Wang et al. 2022d), or excrete as fake feces, interfering with their energy flow (Ma et al. 2020). Previous studies have confirmed a series of negative consequences caused by MPs, such as oxidative stress, stunted growth and reduced fecundity in marine organisms, inhibited photosynthesis in phytoplankton in freshwater environments, and damage in liver organs in animals (Huang et al. 2021; Sun et al. 2022b). After entering the soil, MPs can affect soil properties and communities and their functions, inhibit plant nutrition and growth, and then cause serious damage to agroecosystems (Sun et al. 2022b; Wang et al. 2022b, 2022c, 2022d). MPs can also pose a human health risk through the food chain (Avio et al. 2017; Prata et al. 2020; Huang et al. 2021). Notably, MPs are also found in human blood, placenta, and lungs (Amato-Lourenço et al. 2021; Ragusa et al. 2021; Leslie et al. 2022), posing a potential health risk.

Heavy metals are common environmental pollutants in various ecosystems. Previous studies have found that MPs and heavy metals coexist in marine, freshwater, and soil environments (Turner 2016; Zhou et al. 2019; Khalid et al. 2021). Heavy metals are used as catalysts in plastic production and can release into the environment with the

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decay of MPs (Hahladakis et al. 2018). MPs with small sizes and large specific surface areas can adsorb metals through surface electrostatic interaction, biofilm, or natural organic matter to form new complexes, thus producing a carrier effect on heavy metals (Cao et al. 2021; Gao et al. 2021). MPs can transport heavy metals into living organisms, leading to joint toxicity (Liu et al. 2021a). Co-contamination of MPs and heavy metals can alter soil microbiota and biological processes involved in C and N cycling (Wang et al. 2022c; Salam et al. 2023; Zhang et al. 2023). Co-exposure to MPs and heavy metals can cause severer oxidative stress responses and higher toxicity in higher plants, particularly crops (Kumar et al. 2022; Wang et al. 2022b; Huang et al. 2023), posing a threat to food safety. In particular, MPs carrying heavy metals can enter the bodies of humans and animals through ingestion, inhalation, and skin contact, causing health problems (Cao et al. 2021).

There have been some excellent reviews on the combined pollution of MPs and heavy metals. Kutralam-Muniasamy et al. (2021) reviewed the detection and analysis methods, pollution status, and migration risks of MPs and heavy metals in the environment. Gao et al. (2021) reviewed the behavior and influencing factors of heavy metal adsorption by MPs. Liu et al. (2021a) reviewed the effects of MPs on the mobility, bioavailability, and toxicity of heavy metals. Several excellent reviews have addressed the interactions of MPs and heavy metals in aquatic or terrestrial environments and their combined effects on living organisms and humans (Naqash et al. 2020; Cao et al. 2021; Khalid et al. 2021; Liu et al. 2021b, 2022; Kumar et al. 2022; Khoshmanesh et al. 2023). However, these reviews only focus on one or several particular environmental directions. Bibliometrics can provide a scientific approach to assess research trends from the growth of literature on a particular topic through a visual approach (Li et al. 2022a; Zeb et al. 2022) and can analyze all relevant countries, institutions, journals, authors, references, and keywords in the collected publications (Chen et al. 2016), which can help to understand the current advances, hotspots, and trends of a specific topic in an intuitive way. To our knowledge, no bibliometric analysis has been conducted on the interaction of MPs and heavy metals at a global scale.

In this study, VOSviewer, Pajek64, and CiteSpace were used to analyze the literature on the interactions of MPs and heavy metals. The objective of this study was to visually analyze the current hotspots and trends in MPs and heavy metals, as well as the association or collaboration analysis of leading journals, countries, institutions, and authors. Finally, based on the results and knowledge gaps, we recommended several priority directions. Our results can help the researchers to comprehensively recognize the research advances and future perspectives of this field.

Methodology

Date source and search criteria

The data were obtained by searching the Web of Science Core Collection database from 2008 to July 5, 2022, using the following terms: microplastic * OR nanoplastic * OR micro-plastic OR (nano)microplastic * OR (micro)nanoplastic * AND heavy metal * OR Cu OR Pb OR Zn OR Fe OR Cr OR Cd OR Hg OR Ni OR Mn OR Cobalt OR arsenic. A total of 840 search results were obtained without restrictions of document type or data category. Then, we selected the results by reading their titles and abstracts. Finally, the search results, including complete records in plain text format and cited references, were exported for subsequent data analysis.

Scientometric analysis

To reflect the hotspots and trends of a specific domain in multiple dimensions, VOSviewer (Version 1.6.18), Pajek64 (Portable 5.15b), and CiteSpace (Version 5.8.R3) were used to analyze the document types, years, authors, institutions, countries, journal sources, keywords, and references to form visual network maps. Data were summarized using Microsoft Excel 2016. The importance of node content is represented by the size of nodes and the thickness of lines in the visualization diagram (Padilla et al. 2018). The size of nodes indicates the number or frequency, and the line between nodes indicates the association. A thicker line represents a closer relationship (Gao et al. 2019). Therefore, the research trend can be displayed by analyzing the network visualization graph generated from literature data, and the research prospects can be obtained. Some hotspot articles are also reviewed when we discuss the research progress and knowledge gaps.

Results and discussion

The quantity and type of publications and the dominant journals

A total of 552 articles on MPs and heavy metals were selected for this study, including original research articles (471 items, accounting for 85% of the total number) and review articles (81 items, 15%) (Fig. 1a). The first publication on MPs and heavy metals was published on June 14, 2014, by Holmes et al. in the journal "Marine Chemistry." Since 2019, the number of publications has increased significantly (Fig. 1b, Table S1). From 2014 to 2021, the number of papers grew exponentially (R^2 = 0.9915). In 2021, the

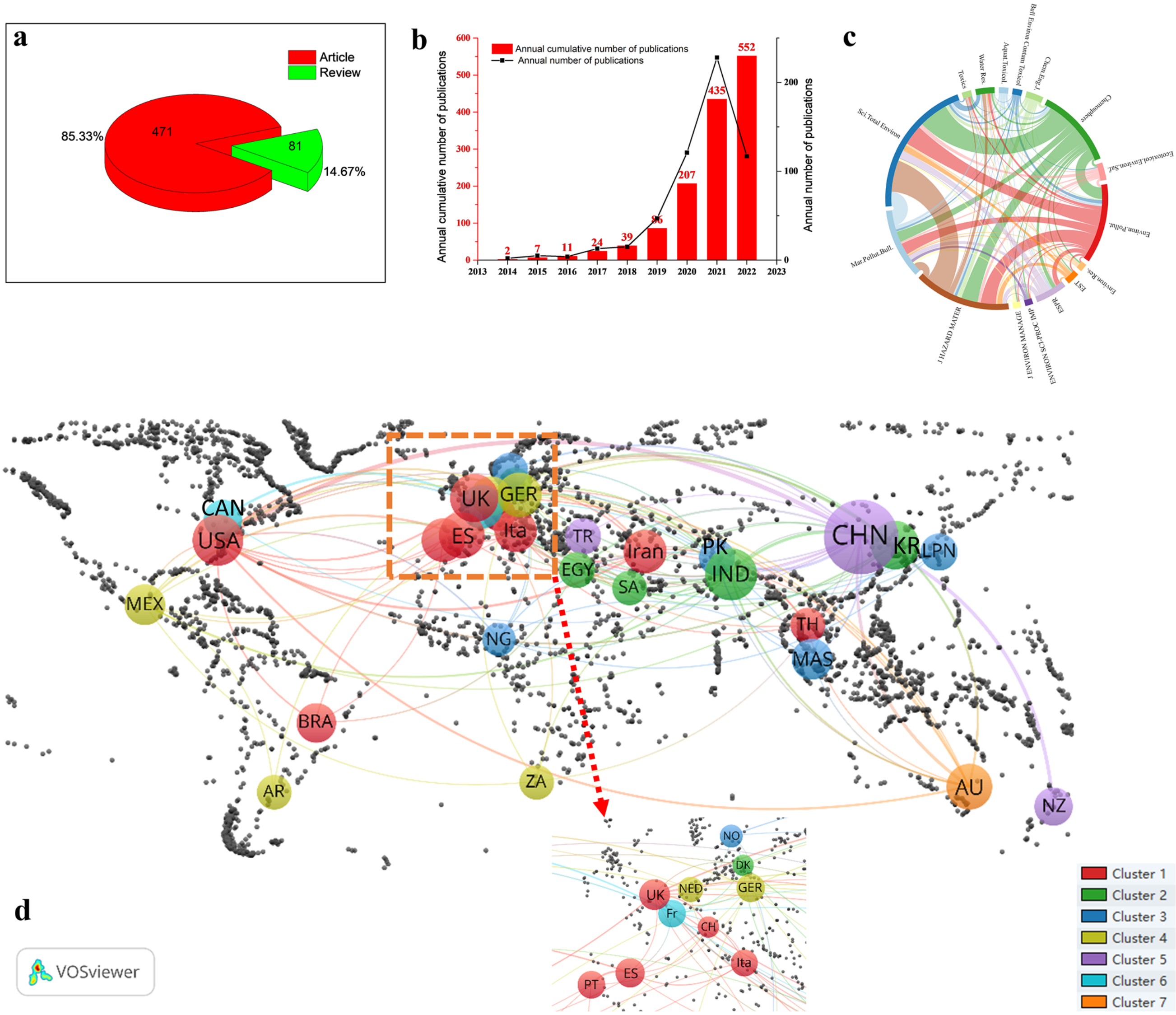

Fig. 1 The number (**a**), document type (**b**), journals (**c**) and country cooperation (**d**). The details of country labels are shown in Tables S3 and S4. The size of the node represents the number of publications; the connecting line represents the cooperation between the countries

annual number of articles published reached 228, accounting for 41.30% of the total number.

These publications were published by a total of 124 journals. The top 16 journals are shown in Fig. 1c and Table S2. There were close citation relationships among these journals. The journal Science of the Total Environment published the highest number of papers (88 papers, accounting for 15.94%), followed by Journal of Hazardous Materials (61, 11.05%), Environmental Pollution (50, 9.06%), Chemosphere (50, 9.06%), and Marine Pollution Bulletin (44, 7.97%). All five journals received citations more than 1000 times.

Contributing countries, institutions, and authors

The authors of the 552 papers come from 841 institutions in 70 countries (Figs. 1 and 2). The partnerships of major contributing countries (top 30) and institutions (top 44) are shown in Table S3, Table S4, and Table S5, respectively. The country with the highest number (267) of published papers is China, accounting for 48.37%, followed by India (47, 8.51%), America (44, 7.97%), UK (34, 6.16%), South Korea (33, 5.98%), Australia (26, 4.71%), and Spain (26, 4.71%). Chinese ACAD SCI has published the most papers (35), accounting for 6.34%, followed by UNIV Chinese ACAD SCI (21, 3.80%), Univ Plymouth (18, 3.26%), Tongji Univ (15, 2.72%), and Hunan Univ (15 papers, 2.72%). As shown in Fig. 1d, the major contributing countries have close cooperation. The publications of the major contributing institutions were published after 2020 (Fig. 2a). The cooperation among the major contributing organizations is limited (Fig. 2c).

The cooperation map of the authors can reflect the current situation of mutual communication and cooperation in the

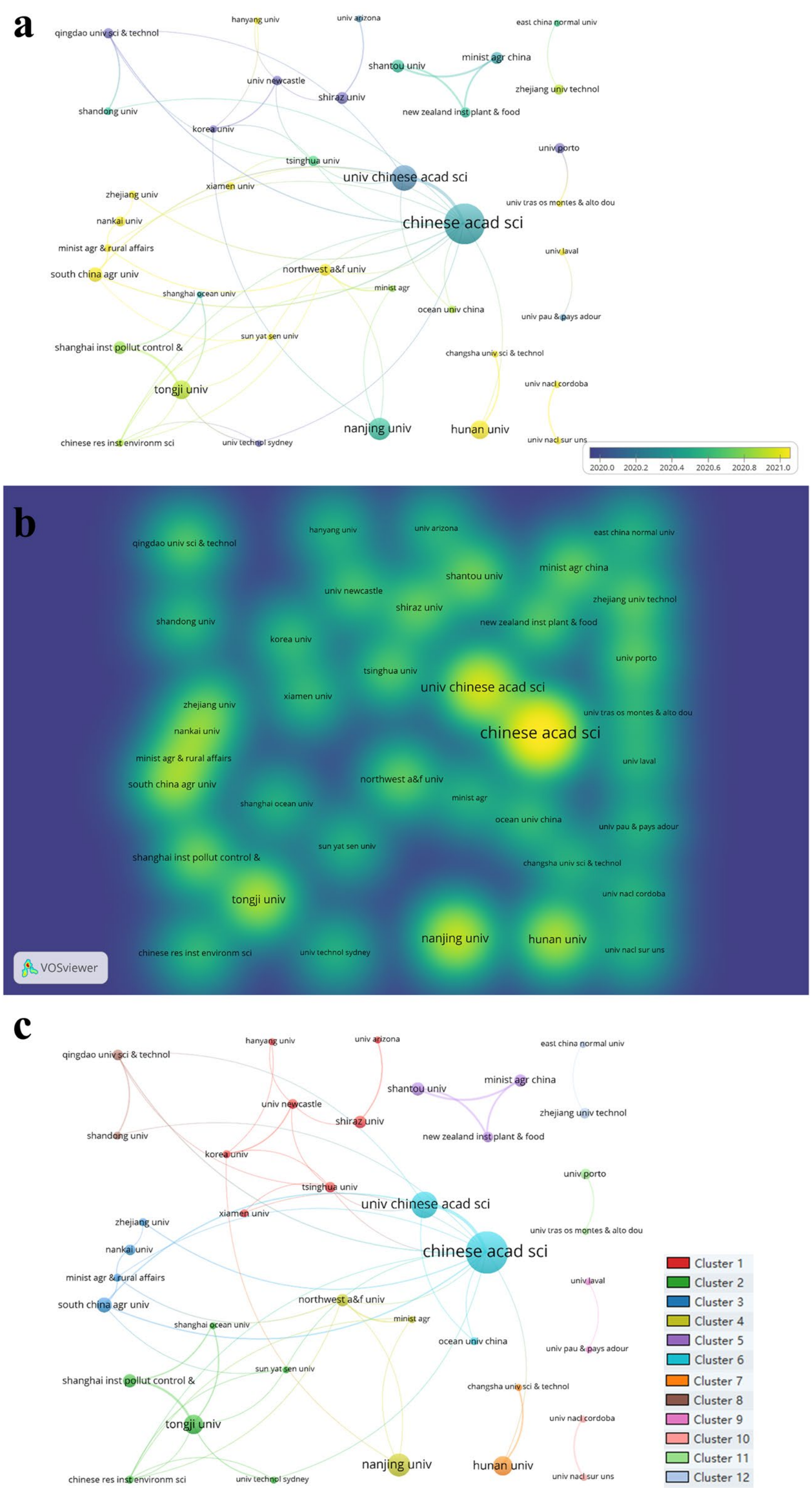

Fig. 2 The overlay (**a**), density (**b**), and network (**c**) of top 44 institutions. The size of the node represents the number of publications; the connecting line represents the cooperation between the institutions

field. A total of 2623 authors contributed to the 552 papers, and 39 authors published more than 5 articles. The author with the largest number of publications (15 papers) is Andrew Turner, from Plymouth University, followed by Zhengguo Song's team (10 papers), and Julien Gigault (9 papers) (Table S6). Among these 39 authors, 32 of them had cooperative papers, particularly in the year 2021 (Fig. 3). These authors' information is shown in Table S6. Figure 3 c shows that there are nine author collaboration clusters, but there is no collaboration among the authors outside of the clusters.

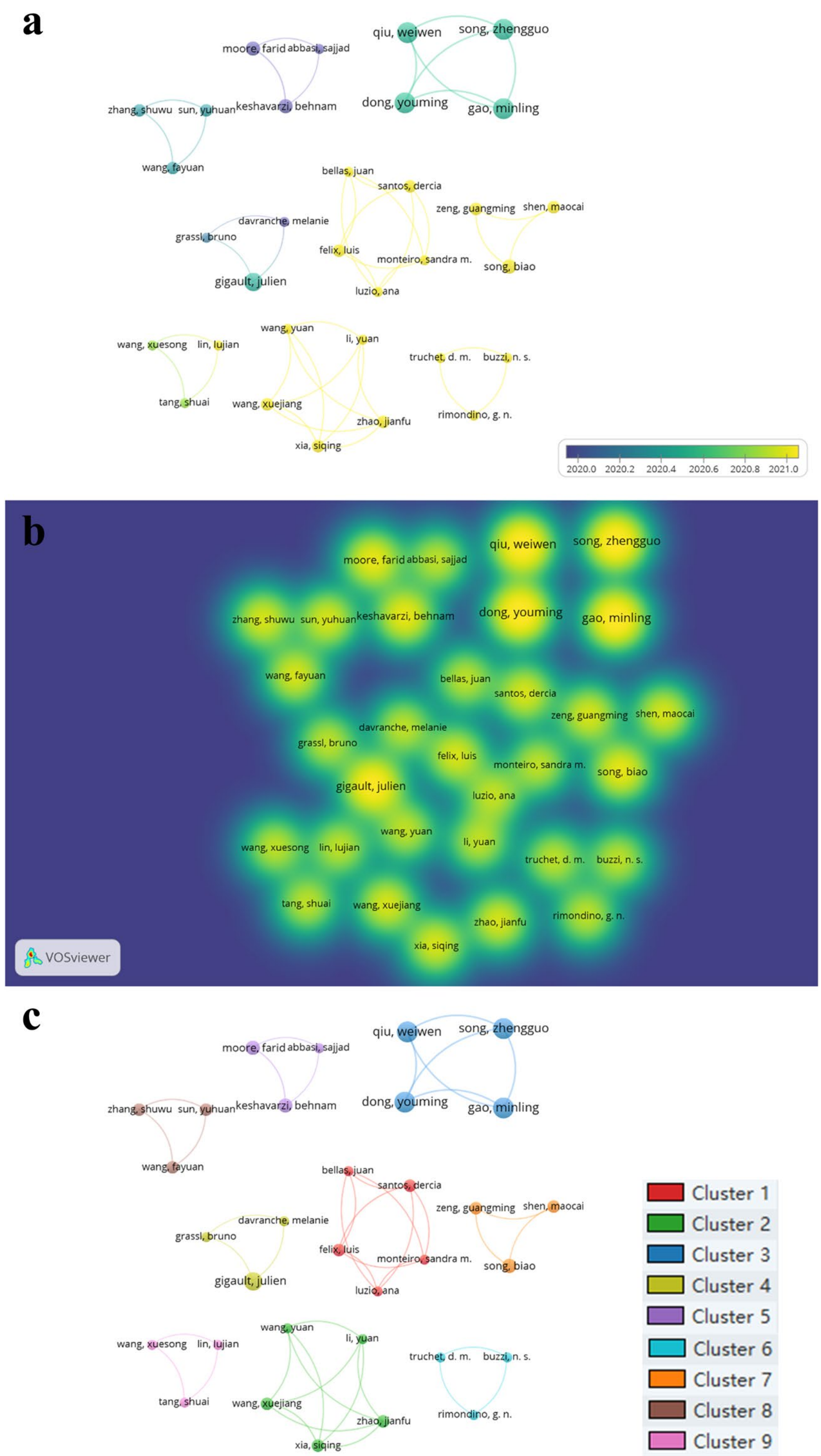

Fig. 3 The overlay (**a**), density (**b**), and network (**c**) of top 39 authors. The size of the node represents the number of publications; the connecting line represents the cooperation between the authors

Annual variation analysis of high co-citation and burst references

Co-citation analysis provides a tool to quantify and visualize the thematic evolution of a specific research area (Cobo et al. 2011). The co-citation of documents was displayed using VOSviewer. Among the 552 articles, their references with more than 50 citations are listed in Table S7. Burst references can reveal the high attention to a research topic in a certain period. Fig. S1 shows the top 25 references with the strongest citation bursts. The annual variation of some important co-cited references in the field of MPs and heavy metals since 2014 is shown Fig. 4 and Fig. S2. Details of these articles are shown in Table S8. By analyzing these

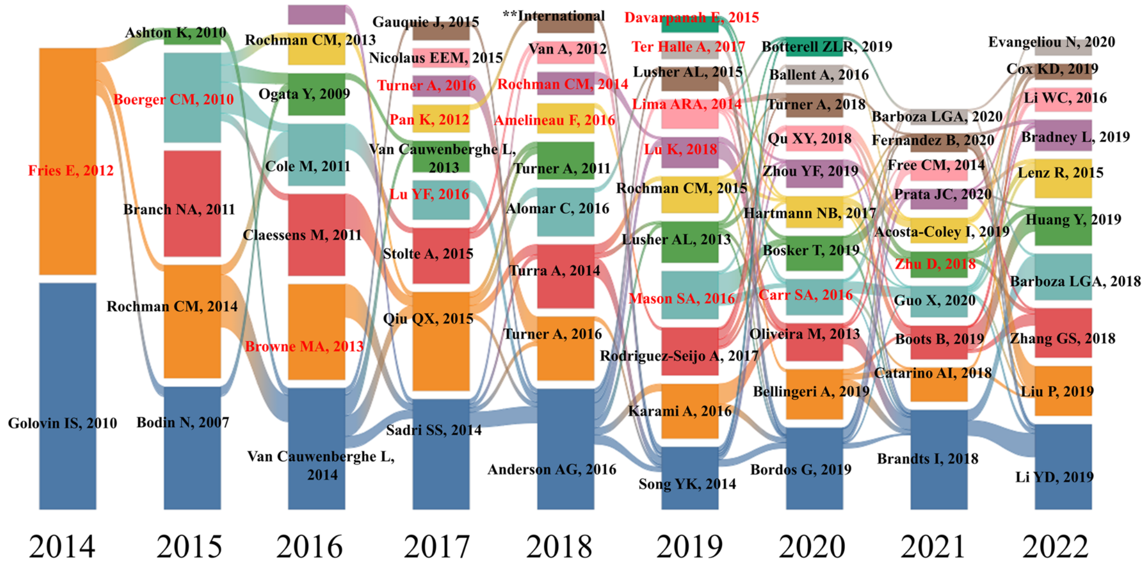

Fig. 4 Annual variation of co-cited references (Sankey diagram, evolutionary process, and citation hotspot change). Red marks represent the first citation of a particular type of research. The wider the connection between the two documents in the figure, the closer the evolutionary relationship is

cited references, several research directions of high concern can be summarized below.

The occurrence and abundance of MPs in the environment and organisms is of the highest priority. The first widely recognized study on MPs was published in Science in 2004, which reported the occurrence of MPs in marine sediments (Thompson et al. 2004). Thereafter, increasing studies have confirmed the occurrence of MPs in aquatic and terrestrial environments (Andrady 2011; Browne et al. 2011; Horton et al. 2017). In general, microplastic abundance is higher in the areas of intensive human activities, such as ports (Claessens et al. 2011) and agricultural soil (Zhang and Liu 2018). The abundance of MPs is also high in the places where material exchange occurs frequently, such as coastlines (Cole et al. 2011; Pan and Wang 2012), estuaries (Nicolaus et al. 2015), and Subtropical Gyre (Ter Halle et al. 2017). One survey found that MPs were distributed in three dimensions in the environment, and even in coastal areas as deep as 2 m underground (Turra et al. 2014). MPs are also widely detected in sewage treatment plants (Mason et al. 2016). It is found that MPs can only be largely removed in the primary treatment process, and secondary and tertiary wastewater treatment cannot effectively remove MPs (Carr et al. 2016). MPs have also been found in more remote areas, such as the deep ocean (Van Cauwenberghe et al. 2013), remote mountain lakes (Free et al. 2014), and the North Pole (Lusher et al. 2015; Amélineau et al. 2016). Meanwhile, MPs can be ingested by a variety of organisms, including marine (Cole et al. 2011) and freshwater organisms (Eerkes-Medrano et al. 2015). The researchers examined the abundance of MPs in fish (Boerger et al. 2010; Lusher et al. 2013) and mussels (Qu et al. 2018), through consuming which humans may have access to large amounts of MPs in their diets (Van Cauwenberghe and Janssen 2014). In an aqueous environment, the density, size, shape, ageing degree, and abundance of MPs will determine their availability to living organisms (Lima et al. 2014; Botterell et al. 2019).

The second hotspot is the adsorption, enrichment, and carrying of heavy metals by MPs. The adsorption of heavy metals by MPs occurs commonly in the environment (Rochman et al. 2014a; Wang et al. 2017). The main mechanism underlying heavy metal adsorption by MPs is electrostatic interaction (Guo et al. 2020). The association of heavy metals with MPs is closely related to the concentration of heavy metals in the environment (Zhou et al. 2019). The ability of MPs to adsorb heavy metals is also affected by pH (Turner and Holmes 2015), temperature (Wang et al. 2020b), surface characteristics of MPs (Avio et al. 2017; Tang et al. 2020), and exposure time (Rochman et al. 2014a). Some studies have found that the aged MPs adsorb much more pollutants than the original MPs (Holmes et al. 2014; Wang et al. 2020b). A field investigation found that MPs can be enriched with dangerous metals, such as Cd and Pb, increasing the risk of metals ingested by organisms (Ashton et al. 2010). MPs can act as carriers of heavy metals and other pollutants, and thus facilitate the transport of pollutants in aquatic environments (Browne et al. 2013; Brennecke et al. 2016; Alimi et al. 2018). MPs effectively increase the intake of Cd, Pb, Br, and Hg by organisms (Turner 2018; Fernández et al. 2020). MPs and related contaminants ingested by low-trophic organisms can be transferred to higher-trophic organisms (Wright et al. 2013).

Third, the toxicity of MPs to animals attracts increasing attention. MPs can accumulate in living organisms and cause inflammation, tissue damage, oxidative stress, neurotoxicity (Brandts et al. 2018), endocrine system function, lipid and energy metabolism, and the expression of genes (Rochman et al. 2014b; Lu et al. 2016; Rodriguez-Seijo et al. 2017; Barboza et al. 2020). MPs can cause physical damage and chemical transfer of toxicants when ingested by organisms (Wright et al. 2013; Eerkes-Medrano et al. 2015;). Co-exposure to MPs and heavy metals can adversely affect living organisms, such as inhibited growth and increased metal accumulation (Barboza et al. 2018; Wang et al. 2022d). A previous study found that polystyrene MPs can enhance the accumulation and toxicity of Cd in zebrafish (Lu et al. 2018).

Another hotspot is the effects of MPs in terrestrial ecosystems (de Souza Machado et al. 2018; Zhang et al. 2022b). MPs can enter and accumulate in soils through multiple pathways, producing ecological effects on soil physical, chemical, and biological properties and soil functionality (Wang et al. 2022c; Zhao et al. 2022a). MPs can interfere with the germination of plants (Bosker et al. 2019), and impede plant growth, inhibit photosynthesis, and interfere with nutrient metabolism, causing oxidative damage and genotoxicity in plants (Zhang et al. 2022b). MPs can change soil properties and soil ecosystem functions via mediating plant growth and earthworm's health (Boots et al. 2019) and soil microbial communities (Huang et al. 2019). As a vector of metals, MPs can increase the exposure of metals to earthworms and improve the bioavailability of metals (Hodson et al. 2017), following which the combined toxicity of MPs and heavy metals in terrestrial ecosystems has become a hotspot attracting wide attention (Khalid et al. 2021).

Cluster analysis of hot keywords

There are a total of 2480 keywords in the 552 papers. We combined some keywords with the same meaning, such as "microplastics (MPs)," "microplastic," and "microplastic pollution" (Table S9). After that, 167 keywords with more than 5 keyword occurrences were used to draw the knowledge graph of the keyword co-occurrence network (Fig. 5). In order to analyze keyword clustering more clearly, we exported map, network, and VOS files of Fig. 5 from VOSviewer, imported them into Pajek, and rearranged them with "Kamada-Kawai" and "In Y Direction" methods to obtain Figs. 6, S3, and S4, respectively.

Understandably, the keyword microplastics has the highest frequency (364 times). Other hot keywords include "metals" (319 times), "adsorption" (159 times), "marine" (151 times), "pollution" (107 times), "sediments" (84 times), "debris" (81 times), "toxicity" (78 times), "contamination" (70 times), "accumulation" (68 times), "cadmium" (63 times), "resin pellets" (63 times), and "nanoplastics" (60 times) (Table S10).

The Overlay map shows the average occurrence year of each keyword (Fig. 5a and Fig. S3). Some keywords appear earlier (green color), such as marine, debris, resin pellet, "chemicals," and "pellets." Some other keywords appear later (yellow color), such as toxicity, "PS-MPs," "soil," "removal," "bioaccumulation," "copper," "arsenic," "zinc," "biofilm," "communities," and "organisms." In particular, the keywords such as microplastics and metals must have appeared early, but the average time is after 2020, indicating the rapid growth of research in this area in recent years, which is consistent with the results in Fig. 1b. The density map shows a density visualization of keywords and hotspot intensities (Fig. 5b and Fig. S4). The keywords with the highest density (red and yellow) are microplastics, metals, adsorption, marine, pollution, sediments, debris, toxicity, contamination, accumulation, "water," resin pellets, cadmium, nanoplastics, and PS-MPs. The Network map shows the co-occurrence relationship of keywords (Fig. 5c). The analysis of high-frequency keywords in each keyword cluster can reveal the research hotspots in the field of MPs and heavy metals from 2014 to 2022. These keywords are divided into six clusters (Fig. 6), and different colors indicate that the keywords belong to different clusters. The detailed information on each hot keyword is shown in Table S10.

Cluster 1 (red) has three core keywords toxicity, accumulation, and fish, indicating that it focuses on the toxicity and accumulation of MPs and heavy metals by organisms (particularly fish). Both MPs and loaded heavy metals can be absorbed by organisms, producing toxic effects. There is a correlation between the metal content in organisms and the metal content adsorbed by MPs isolated from organisms (Zhu et al. 2020), suggesting that MPs can increase the bioaccumulation of heavy metals in living organisms (Yang et al. 2022c). A large number of studies have shown that MPs can aggravate the accumulation of metals in organisms and that co-existing MPs and metals can produce higher toxicity than alone (Lu et al. 2018; Banaee et al. 2019; Wan et al. 2021; Wang et al. 2021b; Luo et al. 2022; Zhang et al. 2022a). For example, polystyrene MPs increased Cd accumulation in zebrafish and co-exposure to Cd and MPs induced oxidative damage and inflammation (Lu et al. 2018). Biofilms can enhance the combined toxicity of MPs and heavy metals (Qi et al. 2021). However, in some cases, due to the adsorption of heavy metals by MPs, the bioavailability of heavy metals is reduced, and the toxicity of heavy metals is delayed (Wen et al. 2018; Wang et al. 2021c).

Cluster 2 (green) mainly focuses on the adsorption of heavy metals by MPs, including the adsorption mechanisms, kinetics, isotherms, and influencing factors. The adsorption behaviors of heavy metals onto MPs are complex, with common sorption mechanisms such as physical and chemical adsorption, electrostatic force and surface complexation, external and internal diffusion, van der

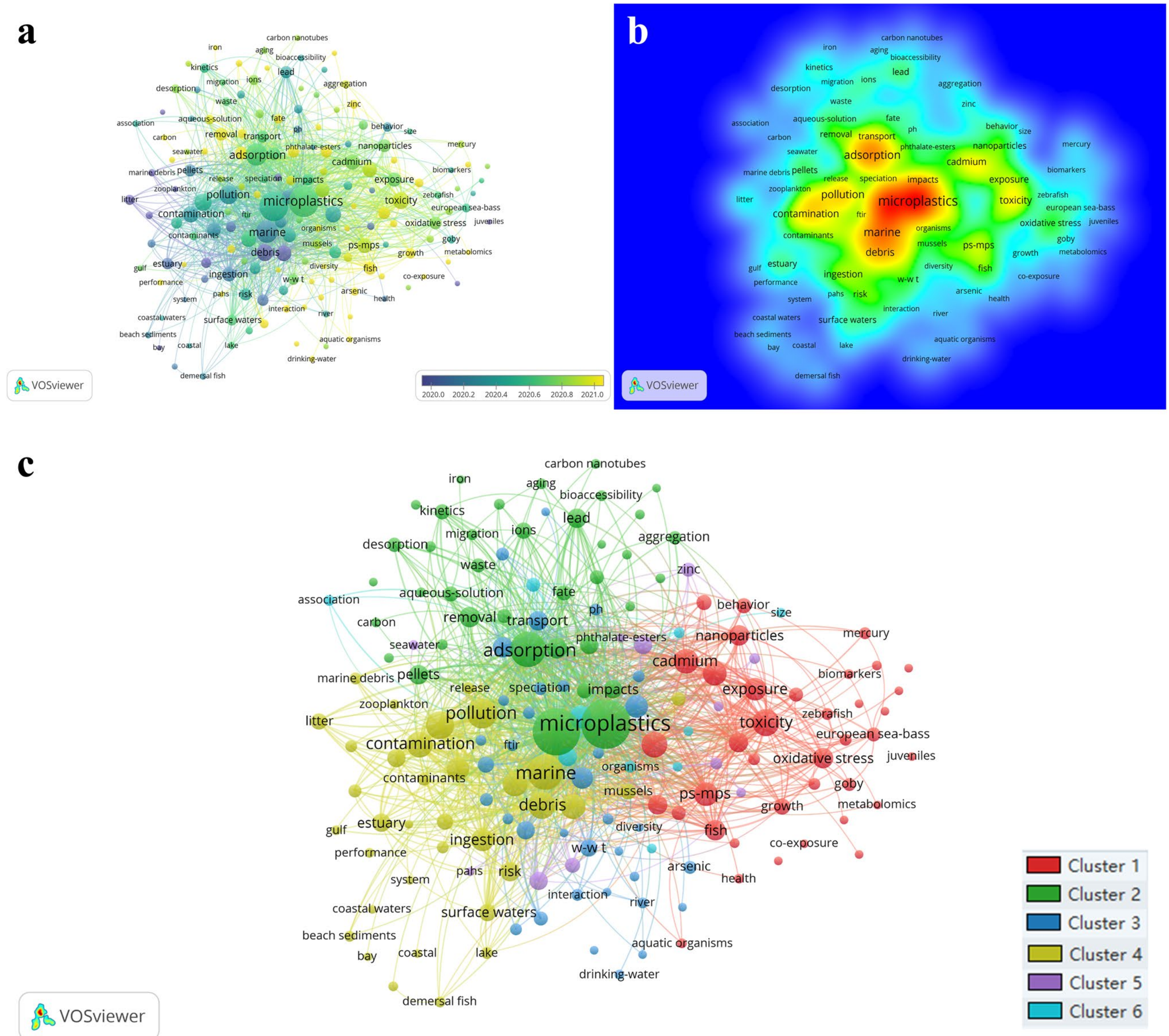

Fig. 5 The overlay (**a**), density (**b**), and network (**c**) of keywords analysis. The size of the node represents the frequency of the keyword; the connecting line represents the total link strength

Waals force, π-π interaction, polar interaction, non-covalent interaction, the pseudo-first- or pseudo-second-order kinetics, and the Langmuir or Freundlich models (Gao et al. 2021). The factors influencing the adsorption behaviors of heavy metals by MPs can be divided into categories: (1) the polymer type, size, dose, and surface characteristics of MPs (Gao et al. 2021), (2) the intrinsic properties and concentration of metals (Dong et al. 2019, 2020; Wang et al. 2019; Tang et al. 2021; Li et al. 2022c), and (3) the environmental conditions, such as the solution pH, temperature, salinity, dissolved organic matter, and particulate matter (Gao et al. 2021). Notably, MPs in the environment will undergo ageing, weathering, and degradation, which can cause a series of changes in surface functional groups, polarity, and surface area, and consequently change the adsorption behaviors of heavy metals (Gao et al. 2021). Due to their low density, MPs can move easily in water and thus increase the transport of the leased metals due to the carrier effect (Liu et al. 2021a). Particularly, MPs reduce the adsorption capacity but increase the desorption of heavy metals by soil, leading to increased mobility of these metals (Zhang et al. 2020; Li et al. 2021). Understandably, soil with MPs may have higher bioavailability and toxicity of heavy metals and increased leaching to water bodies.

Cluster 3 (blue) focuses on how MPs or heavy metals interact with microorganisms and other contaminants (e.g.,

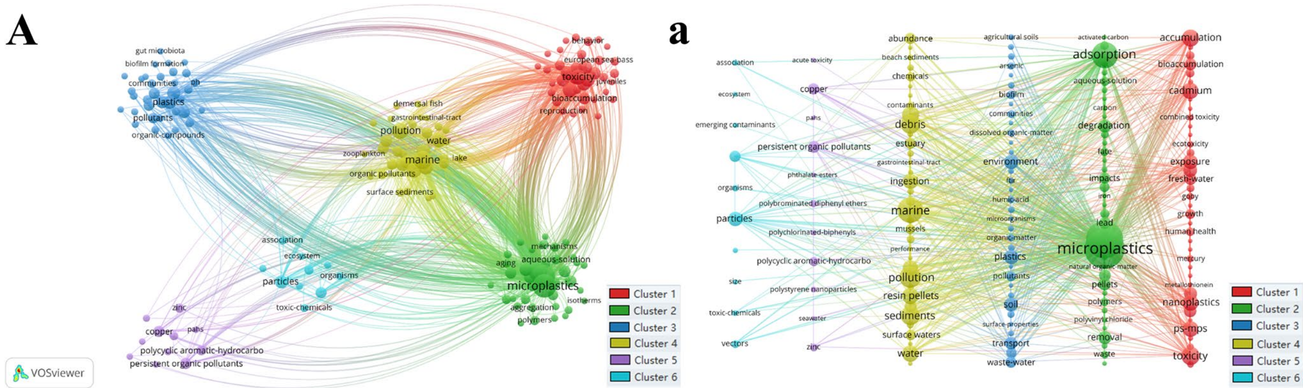

Fig. 6 The network of keyword clusters mapped by "Kamada-Kawai" (A) and "In Y Direction" (a), respectively. The size of the node represents the frequency of the keyword; the connecting line represents the total link strength

antibiotics) in different environments, especially in the soil. MPs can alter the speciation, bioavailability, and toxicity of heavy metals to microorganisms (Wang et al. 2021a; Yang et al. 2022a). The co-occurrence of MPs and heavy metals can modify soil microbial community diversity and structure and their ecosystem functions (Feng et al. 2022; Yin et al. 2022). The ingestion of MPs and heavy metals by organisms increases their intestinal burden and triggers changes in the gut microbial community and functions (Yan et al. 2020; Jiang et al. 2022; Yang et al. 2022b). Biofilms colonizing microplastic surfaces (plastisphere) significantly affect heavy metal adsorption by MPs (Li et al. 2022b). The adsorption of heavy metals by MPs, in turn, affects biofilm formation and ecological functions (Wang et al. 2022a). Microorganisms can influence the fate of MPs (e.g., ageing and degradation) and heavy metals (e.g., transformation and sorption) in the environment, and biofilms have been shown to enhance the transport of metals by MPs and increase their combined toxicity (Qi et al. 2021). Thus, the interactions among MPs, heavy metals, and microorganisms are complex and deserve to be explored.

Cluster 4 (yellow) focuses on investigating and assessing the abundance and risks of microplastic pollution or heavy metals in the aquatic environment. MPs widely distribute in both marine and terrestrial ecosystems, and their surfaces are capable of adsorbing and enriching metals (Li et al. 2020; Patterson et al. 2020). There is a positive correlation between the amount of metal enriched on the surface of MPs and the abundance of metal surrounding them (Zhu et al. 2020). Both MPs and heavy metals, such as Cr, Cd, and As, have been found to contaminate water and sediments (Mohsen et al. 2019; Jahromi et al. 2021; Sun et al. 2022a). Heavy metals and MPs have also been detected in aquatic animals, such as bivalves, oysters, sea cucumbers, and fish (Mohsen et al. 2019; Zhu et al. 2020; Jahromi et al. 2021; Vieira et al. 2021; Sun et al. 2022a). Since many of these animals are consumed as sea foods by humans, their ingestion of MPs and associated heavy metals will bring enlarged health risks for consumers.

The core keywords in cluster 5 (purple) are pollutants such as persistent organic pollutants and polycyclic aromatic-hydrocarbons, indicating that it is concerned with the interrelationship of MPs or heavy metals with other pollutants in the environment. In many cases, MPs or heavy metals do not singly exist in the environment but co-exist with other pollutants, such as organochlorine pesticides and polycyclic aromatic hydrocarbons (Fred-Ahmadu et al. 2022). These pollutants are even ingested together by living organisms (Borges-Ramírez et al. 2021; Hu et al. 2022; Xiang et al. 2022). Similar to heavy metals, organic pollutants can adsorb and interact on the surface of MPs. For example, the presence of other pollutants alters the adsorption behavior of heavy metals by MPs (Yu et al. 2020; Zhao et al. 2022b). Co-exposure of MPs and heavy metals with a variety of other contaminants can lead to complex toxicity to organisms (Menéndez-Pedriza and Jaumot 2020; Xiang et al. 2022), making it difficult to investigate the interactions of MPs and heavy metals. It is also challenging to assess the biological toxicity of multiple pollutants.

Cluster 6 (cyan) focuses on the identification and characterization of MPs (and heavy metals) in the environment. Understanding the abundance of MPs in the environment and the concentration of metals on the surface of MPs is a prerequisite for further study of their interactions (Mohsen et al. 2019; Kutralam-Muniasamy et al. 2021). MPs and nanoplastics are considered a type of new pollutants for which analytical methods still need to be developed. The separation, identification, and classification of MPs (i.e., polymer type, particle size, shape, color) are difficult due to their small size and the fact that they can aggregate or interact with other environmental media (Bitencourt et al. 2020; Tirkey and Upadhyay 2021). Although analytical methods for heavy metals are relatively mature (Inobeme et al. 2023), it is difficult to separate smaller MPs (e.g., nanoplastics) from environmental samples such as soils, causing challenges in the identification and quantification of the associated metals. The future development of high-throughput and standard methods to identify and accurately characterize MPs and the associated heavy metals would therefore be a ground-breaking initiative (Kutralam-Muniasamy et al. 2021).

Timeline view of keywords co-occurrence network and burst keywords analysis

The keyword co-occurrence network represents the static scene, but cannot display the dynamic changes in the study area. The timeline view and burst keywords can illustrate the evolution of keywords. The size of the node indicates the frequency of keyword occurrences. The colored lines connecting two nodes represent their co-occurrence relationship (Wang et al. 2020a).

Fig. S5 shows the evolution of keywords from 2014 to 2022. The adsorption behaviors of metallic pollutants onto MPs are the most frequent topic, accompanied by the keywords like pollution and accumulation. In addition to the appearance of individual metal elements, keywords such as cadmium, bioaccumulation, and toxicity are also mentioned during this period. Over time, the keywords such as risk, ecosystem, and "food web" appeared, indicating that the research areas continued to expand.

To display hot topics, Fig. S6 shows the 10 keywords with strength greater than 2, as well as the 10 keywords with strength less than 2 but expected to be hot topics in the future. Debris and "litter" are among the hot keywords. Subsequently, the marine environment, the water environment, the type of plastic particles, and the toxicity have become hot topics. In 2021, researchers started to shift their focus from local phenomena to global impacts, as shown by the emergence of ecosystem. The transfer of MPs and heavy metals through the food web is also a current hotspot. MPs and related contaminants can potentially have long-term effects on biological and human health through the food web and dietary exposure (Huang et al. 2021).

To conclude, MPs and heavy metals have been extensively studied in aquatic (particularly marine) environments, but the data from studies in soil and atmospheric environments are relatively lacking. The ecotoxicological studies of MPs and heavy metals on food webs and ecosystems are worth exploring.

Conclusions and future directions

Using a bibliometric analysis based on VOSviewer, Pajek64, and CiteSpace, the background of knowledge, research performance, and the latest knowledge structure on MPs and heavy metals over the last 9 years were presented and reviewed. A total of 552 articles have been published in 124 journals, such as Science of the Total Environment, Journal of Hazardous Materials, Environmental Pollution, Chemosphere, and Marine Pollution Bulletin. There are 39 authors having more than 5 articles, and Andrew Turner, from Plymouth University, published the largest number of publications (15 papers). A total of 70 countries have published articles related to this field, with China making the largest contribution. The leading institutions and authors have close collaborations. The analysis of the total highly cited literature shows that the hotspots are shifting from marine to terrestrial ecosystems, with focus on the exploration of toxicity mechanisms. Hot keyword analysis shows that the research on MPs and heavy metals has focused on their toxicity and bioaccumulation, the adsorption and desorption behaviors, the environmental pollution and risk assessment, and their detection and characterization.

Based on the current bibliometric analysis of the research history and current status of MPs and heavy metals, the following directions for future research should be highlighted.

1. Both MPs and heavy metals are persistent in the environment. Considering the spatiotemporal heterogeneity of MPs and heavy metals in the environments, one of the priority directions is to investigate their co-occurrence, source, characteristics, and environmental fate and behaviors, especially in terrestrial ecosystems and soil environments that have not been unveiled sufficiently. MPs with smaller sizes (e.g., nanoplastics) and aged surface generally have a stronger ability to adsorb and enrich heavy metals, which deserve more concern.
2. Analytical methods should be developed and standardized for effective extraction and accurate quantification of MPs (particularly nanoplastics) and the associated heavy metals from various environmental samples.
3. Most current studies on the interaction of MPs and heavy metals are focused on aquatic (marine) organisms and ecosystems. However, MPs and heavy metals are both common contaminants in terrestrial ecosystems, particularly agroecosystems, posing threats to food safety and security. The co-contamination effects and toxicity of MPs and co-existing heavy metals on terrestrial crops and soil biota should be addressed in future work. There is a need to gain insight into their toxicological mechanisms on organisms using multi-techniques, such as omics (e.g., genomics, transcriptomics, proteomics, and metabolomics).
4. The impact of MPs on the bioavailability and bioaccessibility of heavy metals and the ability of MPs and heavy metals to be transported along food webs through trophic levels need to be further investigated. It is expected that the ingestion and bioaccumulation of MPs may release the associated heavy metals from organisms to the food chain, and thus biomagnify across trophic levels, posing uncertain ecological and health risks.
5. MPs and heavy metals co-occur in the atmosphere and foods and drinking water, thus entering human bodies

through inhalation and ingestion (Al Osman et al. 2019; Pironti et al. 2021). Although the presence of MPs in human tissues and their health risk have been reported, the combined toxicity mechanisms and health risks of MPs and heavy metals have not been well elucidated.

6. Finally, sustainable strategies are needed to reduce pollution from MPs and heavy metals, such as the use of policy, legislative and regulatory, and environmental interventions in promoting the reduction, reuse, and recycling (i.e., 3Rs) of plastic and metallic wastes, and the development of biodegradable plastics to replace non-degradable polymers.

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