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Research progress and hotspot analysis of soil microplastics: a bibliometrics-based review

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Microplastics are ubiquitous in soil ecosystems, and they have attracted widespread attention owing to their accumulation, migration and diffusion in soil environments and their negative effects on the environment and human health. However, previous studies on microplastics have predominantly concentrated on aquatic environments, and their presence in soil ecosystems has seldom been studied systematically. This review presents a systematic analysis of the current research on soil microplastics based on the available literature from 2016 to 2023 using CiteSpace. The most influential journals, authors and countries in this field were identified. Keyword co-occurrence analysis was performed to determine research hotspots, and cluster analysis was employed to provide an accurate summary of this field. Furthermore, burst detection was used to explore research fronts. This review reveals the increasing depth and diversity of research on soil microplastics and discusses potential research fronts for future studies in this field.

KEYWORDS

bibliometric analysis, Citespace, microplastics, soil, visualized analysis

1 Introduction

The widespread use of plastic products has greatly facilitated the productivity and daily life of people, but it also poses serious environmental problems. Global plastic production has risen exponentially from 1.5 MT in 1950 to 359 MT in 2018, and it is projected to reach 670 MT in 2040 (Delangiz et al., 2022). However, only 9% of the plastics are recycled each year (Yao et al., 2023). Discarded plastics gradually break down into smaller fragments and particles due to long-term microbial mediation or environmental factors such as wind, ultraviolet radiation, water and ice. Thompson et al. (2004) introduced the term “microplastics” in their paper on plastic debris in seawater and sediments. Microplastics are now typically defined as plastic debris and particles with a diameter of less than 5 mm, and they have attracted significant attention as novel environmental pollutants (Machado et al., 2018a). Microplastics have been detected in various ecosystems, including marine (Zhou et al., 2022), freshwater (Talbot and Chang, 2022), terrestrial (Wang et al., 2022) and airborne (Chandrakanthan et al., 2023). The United Nations Environment Programme (UNEP) has recognised microplastics as a significant emerging pollutant due to their small size, widespread distribution and long-lasting presence in the environment (UNEP, 2010; Su et al., 2019; Selonen et al., 2020).

Abbreviations: AFM, Atomic force microscopy; ARG, antibiotic-resistant genes; DSC, Differential scanning calorimetry; NIR, Near-Infrared; TS, Topic Search; UNEP, United Nations Environment Programme; WOSCC, Web of Science Core Collection.

Soil is a natural resource that is necessary for human survival and is threatened by microplastic pollution. However, while many studies have focused on microplastics in aquatic environments, research on soil microplastics started relatively late and is still in its early stages. Rillig (2012) were one of the first groups to publish an article calling attention to microplastic pollution in terrestrial ecosystems. Further research has led to the development of new technologies for quantifying and identifying microplastics in soil (Elert et al., 2017; Bläsing and Amelung, 2018). Microplastic pollution has been reported to be more prevalent in soil than in the ocean by four to 23 times (Chen et al., 2020). Microplastics may accumulate, migrate and diffuse in soil (Li et al., 2021), and they can affect soil ecosystems by interfering with the carbon and nitrogen cycling (Rillig et al., 2021; Rong et al., 2021). The leaching of additives that may be carcinogenic or endocrine disruptors can also cause toxicological harm (Lambert et al., 2014; Liwarska-Bizukojc, 2021). Microplastics can absorb and act as a vector for organic pollutants, heavy metals, antibiotic-resistant bacteria and antibiotic-resistant genes (ARGs) (Liu et al., 2021; Zhang et al., 2022). Thus, microplastic pollution has gradually become an urgent environmental and health problem.

Research on soil microplastics has been rapidly expanding the understanding of their distribution, identification and toxic effects. However, a systematic analysis of the research progress and hotspots of soil microplastics as a field is still lacking. Such a systematic summary will serve as an important reference for understanding and preventing the negative effects caused by microplastics in soil environments. We conducted a bibliometric analysis on a Web of Science database from 2016 to 2023 to systematically review the current state of the literature on soil microplastics. Based on our analysis, we identified the knowledge structure, development context, hot topics and developing trends in soil microplastics research, and we explored possible opportunities and challenges for the future. We expect our review to provide a theoretical basis for the research and management of soil microplastics.

2 Methodology

2.1 Data collection

The Web of Science Core Collection (WOSCC) was selected as the database for analysis. The search terms were set to TS (Topic Search) = (“microplastics” AND “soil”). Original articles were selected without considering papers from proceedings or conferences and book chapters. The search was conducted on 1 April 2023, and the retrieved papers were published from 2016 to 2023. The data retrieval started in 2016 because there were no results for soil microplastics published before 2015 in WOSCC database. All retrieved papers were manually checked to remove irrelevant documents, and 1,627 papers were kept. All records, including titles, abstracts and cited references, were exported as a pure text file for subsequent analysis.

2.2 Scientometric analysis

CiteSpace is a Java-based scientific visualisation software used for science mapping and scientific domain visualisation designed

by Chen et al. (2006). CiteSpace provides various functions for exploring knowledge maps, including identifying the contributing authors, countries and journals, research hotspots and research fronts. We used CiteSpace (Version 6.2. R3) to analyse the frequency of studies on soil microplastics between 2016 and 2023. The time span was set to January 2016–April 2023, the time partition was 1 year, and the selected node types were author, country and keyword. The cropping method was selected as a pathfinder to prune sliced and merged networks. The rest of the settings were left at their default, and co-occurrence and clustering analyses were performed. In the obtained knowledge map, a node represented one item, such as a keyword, journal or reference. The links described the co-citation or co-occurrence between these nodes (Xie, 2015). Each node was represented by tree rings of varying thickness, indicating the number of citations and different colours representing the publication years of the literature cited (i.e., blue for oldest and orange for latest) (Ouyang et al., 2018). Nodes with high centrality were highlighted with a purple ring to better identify pivotal points (Freeman, 2008). The flow diagram of the study design is shown in Figure 1.

3 Results

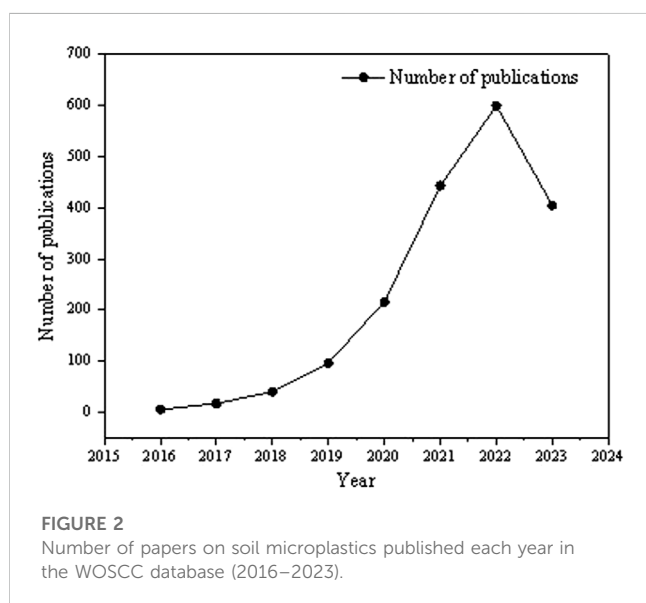
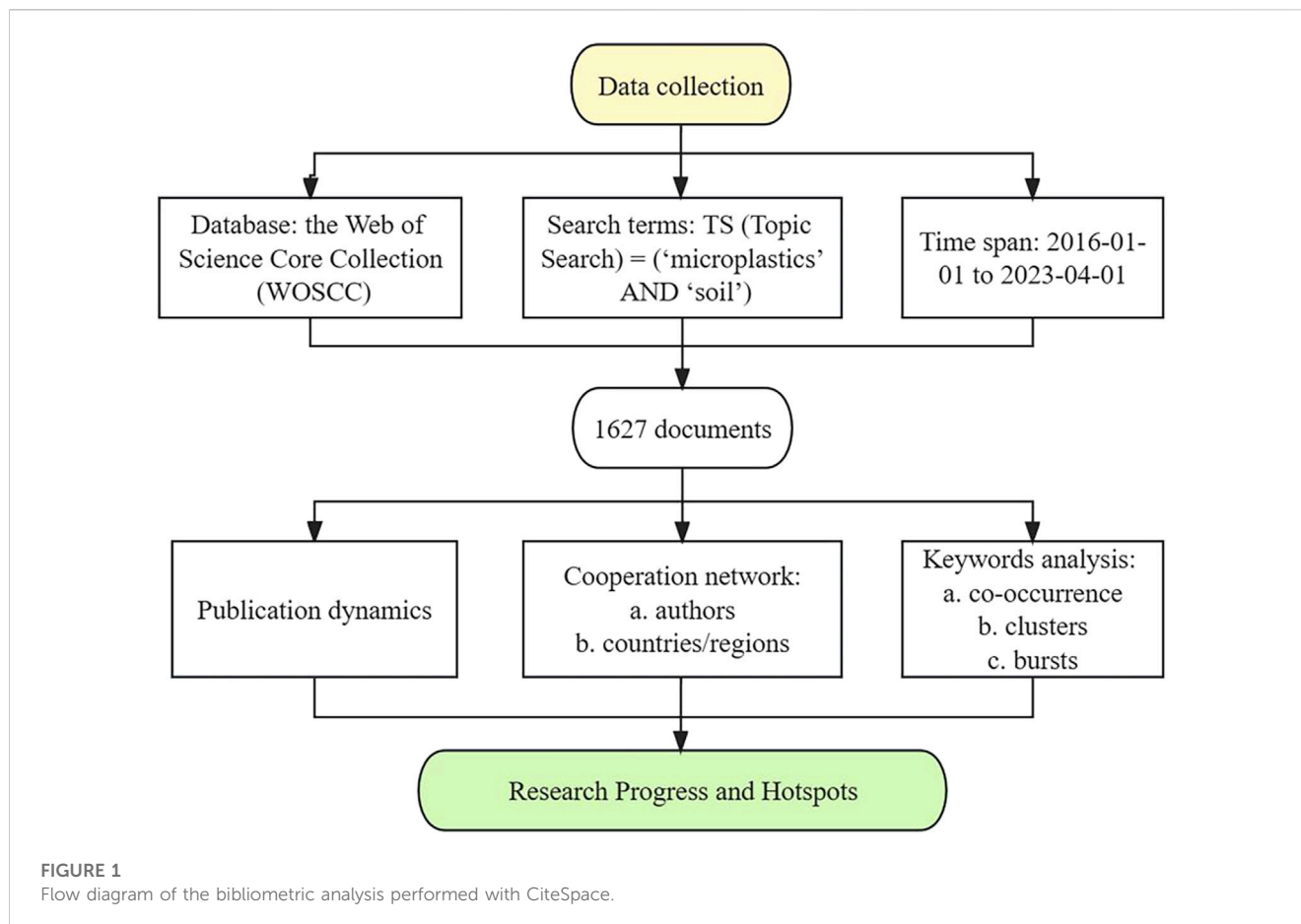
3.1 Basic characteristics of the publications

3.1.1 Publication dynamics

We analysed the number of papers published each year to determine the general trend of soil microplastics research, as shown in Figure 2. In total, 1,627 papers related to soil microplastics were published between 2016 and 2023. From 2016 to 2018, no more than 50 papers were published each year, which we classified as a slow development stage. Several papers with a high citation frequency were published during this state, which helped the public become aware of the potential harm caused by microplastics in soil (Steinmetz et al., 2016; Machado et al., 2018b; Chae and An, 2018). During this stage, researchers mostly focused on analytical methods (Shan et al., 2018; Zhang SL et al., 2018), occurrence (Liu MT et al., 2018; Scheurer and Bigalke, 2018; Zhou et al., 2018), potential damage to soil organisms (Deng et al., 2017; Lwanga et al., 2017; Zhu D et al., 2018) and soil ecosystems (Machado et al., 2018a). Some papers focused on the interaction of microplastics with other pollutants, but the literature was limited (Hodson et al., 2017; Liu J et al., 2018). From 2019 to 2022, soil microplastics gradually gained significant attention, and the number of papers published each year increased rapidly, which we classified as a rapid development stage. In 2022, 600 papers were published, which is approximately three times the 216 papers published in 2020 and six times the 96 papers published in 2019. These results indicate that research on soil microplastics has entered a stage of rapid growth and diversification.

3.1.2 Journal distribution

The key journals of a field can be identified from the distribution of related papers. Table 1 lists the 10 journals that published the most papers related to soil microplastics. Together, these journals published 781 papers or 55.04% of all retrieved



papers. The four journals with the most published papers were *Science of the Total Environment*, *Journal of Hazardous Materials*, *Environmental Pollution* and *Chemosphere*. All these journals had an impact factor of greater than 5. The four journals with the greatest impact factors were the *Journal of Hazardous Materials*, *Water Research*, *Environmental Science*

and *Technology and Science of the Total Environment*. Overall, the key journals for soil microplastics were determined as *Science of the Total Environment*, *Journal of Hazardous Materials*, *Environmental Pollution* and *Chemosphere* in terms of quantity and influence.

3.2 Cooperative network analysis

Co-author analysis was conducted to identify the major authors and their cooperative relationships. Figure 3 shows the cooperative network among authors. The node size indicates the influence of an author, and the links between nodes indicate a cooperative relationship between authors. A thicker link indicates a closer relationship. The most influential authors in the field of soil microplastics were identified as Matthias C. Rillig (Germany), Violette Geissen (Netherlands) and Luo Yongming (China). Closely cooperating research teams were also identified. The research team, with Matthias C. Rillig as the core and including Kim Shin Woong, mainly studied the effects of microplastics on nematodes in a soil environment (Kim et al., 2021a; Kim et al., 2021b). Violette Geissen and her research team mainly focused on the effects of microplastics on soil microbiomes as well as in agricultural soil. Luo Yongming and his research team, including He Defu, mainly carried out comprehensive reviews on soil microplastics. Overall, the authors in this field were closely linked with frequent communications.

TABLE 1 Top-10 journals based on number of publications.

Journal	Number of documents	Percentage of total literature (%)	Impact factor
<i>Science of the Total Environment</i>	244	16.82	10.754
<i>Journal of Hazardous Materials</i>	139	9.58	14.224
<i>Environmental Pollution</i>	121	8.34	9.988
<i>Chemosphere</i>	82	5.65	8.943
<i>Water Air and Soil Pollution</i>	46	3.17	2.984
<i>Environmental Science and Technology</i>	38	2.62	11.357
<i>Environmental Science and Pollution Research</i>	32	2.21	5.190
<i>Environmental Research</i>	30	2.07	8.431
<i>Water Research</i>	27	1.86	13.400
<i>Ecotoxicology and Environmental Safety</i>	22	1.52	7.129

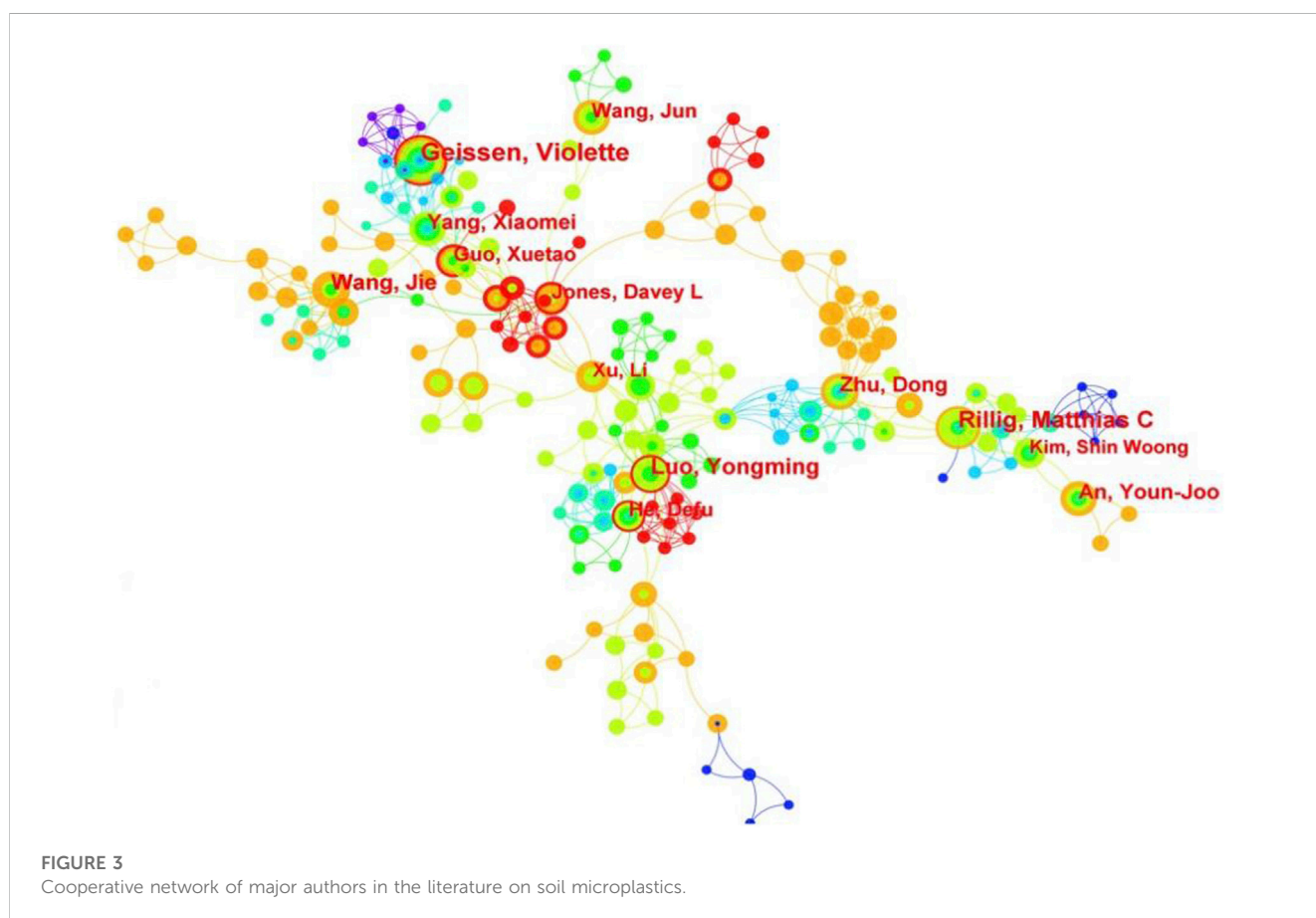


FIGURE 3 Cooperative network of major authors in the literature on soil microplastics.

Figure 4 shows the cooperative network among countries, which helps with understanding the geographic distribution of studies on soil microplastics. The ring size indicates the number of papers published by each country, and the links between countries indicate a cooperative relationship. Most research on soil microplastics has taken place in China (frequency = 826), followed by the United States (frequency = 180), Germany

(frequency = 132), Australia (frequency = 106) and India (frequency = 81). Moreover, countries have closely cooperated with each other on soil microplastics. For example, the links between China and Germany, the United States and India, Australia and South Korea are relatively close and complex, indicating a closer cooperative relationship between these countries.

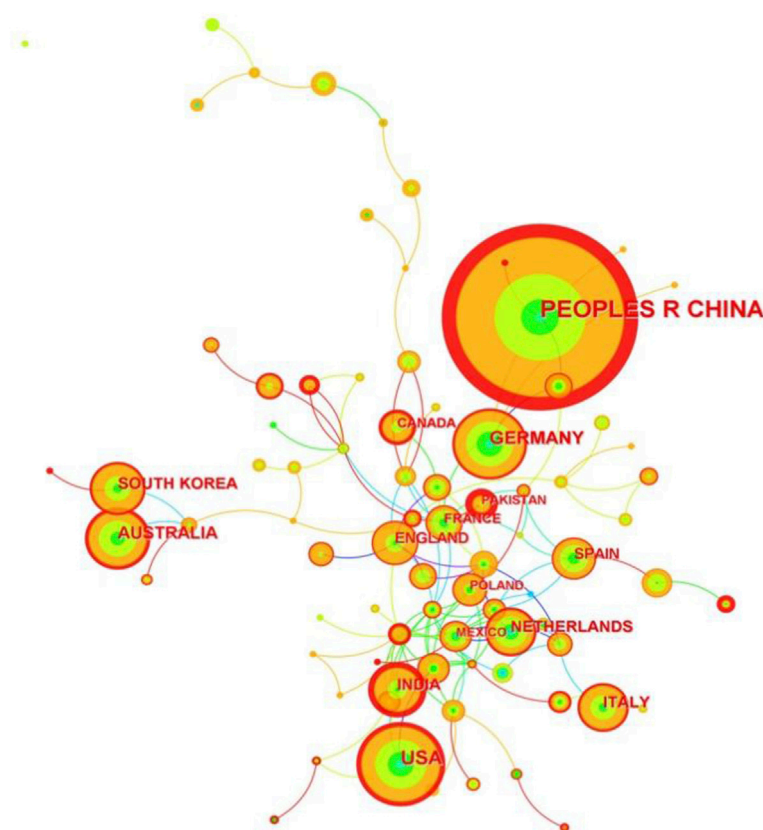


FIGURE 4
Cooperative network of countries/regions for the literature on soil microplastics.

3.3 Keywords co-occurrence analysis

Keyword co-occurrence analysis is often used to explore research hotspots in a particular field. Figure 5 shows the results of the keyword co-occurrence analysis on soil microplastics. In total, 487 nodes and 1,509 links were detected. The first paper on soil microplastics was published by Rillig (2012). However, owing to the complexity of soil environments and the limitations of detecting microplastics in soil, research on microplastics has predominantly focused on aquatic environments. This explains the prominence of the keywords “water,” “fresh water” and “marine environment”. Table 2 lists the keywords related to soil microplastics and excludes those irrelevant keywords to identify the research hotspots. The most frequent keywords were “pollution” (frequency = 427), “microplastics” (frequency = 343), “soil” (frequency = 225), “plastics” (frequency = 186) and “particles” (frequency = 186). The centrality measures how much a node affects the shortest path between other nodes, and a higher centrality value indicates more influence (Zeb et al., 2022). The keywords with the highest centrality were “analytical methods” (centrality = 0.20), “organic pollutants” (centrality = 0.19), “community structure” (centrality = 0.19), “organic matter” (centrality = 0.14) and “ingestion” (centrality = 0.14). With regard to trends over time, research on soil microplastics has clearly expanded from an initial focus on pollution, identification and quantification to include fate, exposure toxicity, adsorption, biodegradation and bioaccumulation from 2016 to 2023.

3.4 Cluster analysis

We conducted a cluster analysis on keywords to clarify the different directions adopted by the research on soil microplastics. Figure 6 shows that research on soil microplastics can be divided into 12 clusters. Table 3 lists the clusters and their ID, size, silhouette, cluster label and respective keywords. Clusters #0 and #2 are focused on conventional and biodegradable microplastics. Conventional plastics are widely used in packaging, agricultural films, biomedical materials and 3D printing, but they have caused serious environmental pollution. With the increasing awareness of sustainable development, biodegradable plastics are gaining attention as a potential substitute (Wang et al., 2022). Biodegradable plastics comprise natural or microbial-secreted polymers that can be converted into H₂O, CO₂ and biomass through biological activity under suitable conditions (e.g., temperature, humidity and microorganisms) (Rujnic-Sokele and Pilipovic, 2017). However, biodegradable plastics have the same lifespan as conventional plastics if the degradation conditions are not met, and they may disintegrate into microplastics more rapidly than conventional plastics. Thus, they have emerged as another threat to the environment (Wei et al., 2021). Moreover, the separation and extraction standards; environmental behaviour and ecological effects; impact on microorganisms, soil fauna and plants; and adsorption and desorption of toxic substances onto biodegradable microplastics remain to be studied.

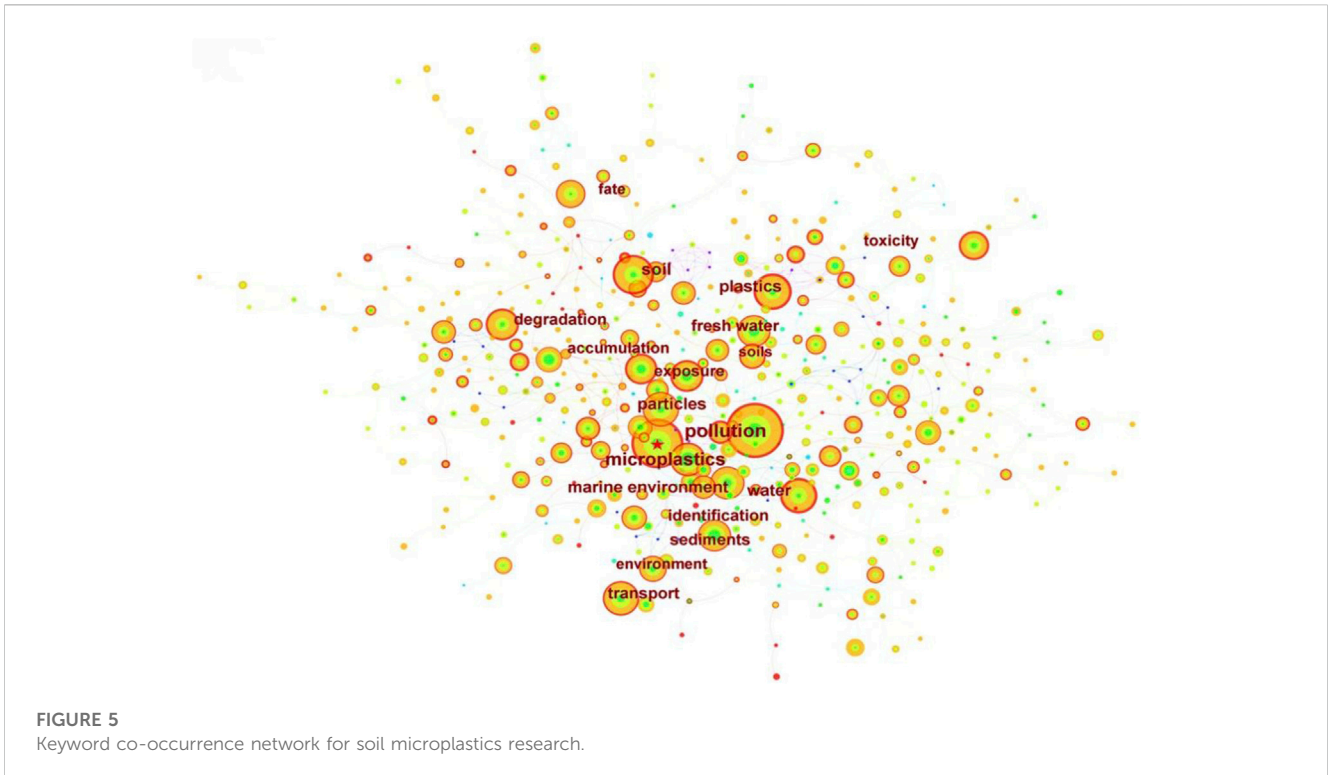


TABLE 2 Top-20 keywords in soil microplastics research ranked by frequency and centrality.

Ranking	Keywords	Year	Frequency	Keywords	Year	Centrality
1	Pollution	2016	427	Analytical methods	2018	0.20
2	Microplastics	2016	343	Organic pollutants	2019	0.19
3	Soil	2017	225	Community structure	2019	0.19
4	Plastics	2016	186	Organic matter	2016	0.14
5	Particles	2016	186	Ingestion	2016	0.14
6	Transport	2018	171	Plastics	2016	0.13
7	Identification	2016	169	Diversity	2017	0.13
8	Degradation	2017	166	Litter	2016	0.13
9	Sediments	2017	152	Quantification	2016	0.12
10	Exposure	2018	148	Desorption	2020	0.12
11	Accumulation	2017	136	Environmental samples	2018	0.11
12	Toxicity	2018	128	Extraction	2017	0.11
13	Fate	2018	124	Pollutants	2016	0.11
14	Sewage sludge	2018	93	Plastic mulch	2019	0.11
15	Organic matter	2016	88	Fractions	2020	0.11
16	Sorption	2019	87	Behaviour	2018	0.10
17	Nanoplastics	2016	85	Bioaccumulation	2017	0.10
18	Heavy metals	2019	83	Carbon nanotubes	2018	0.10
19	Biodegradation	2017	81	Exposure	2018	0.09
20	Agricultural soils	2017	76	Ecosystems	2016	0.09

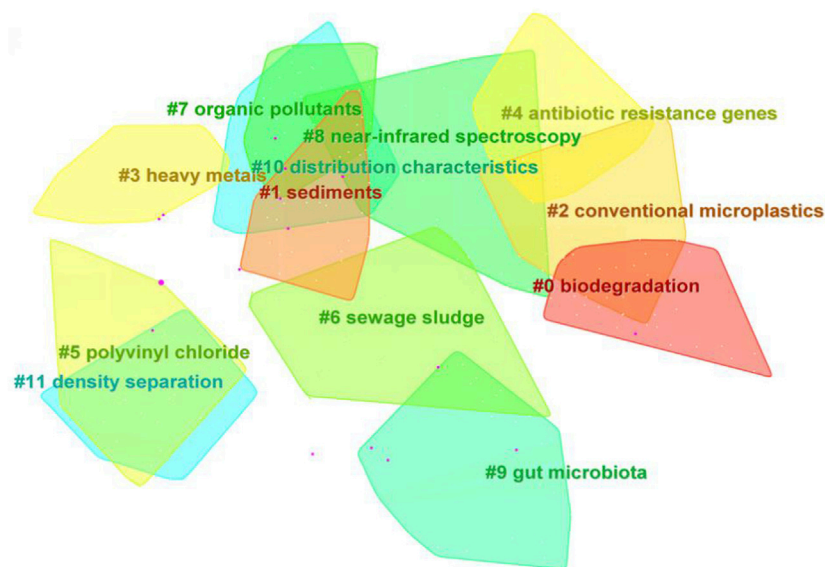


FIGURE 6
Keyword cluster atlas of soil microplastics in the WOSCC.

TABLE 3 Knowledge clusters in soil microplastics research based on keyword co-occurrence.

Cluster ID	Size	Silhouette	Cluster label	Top terms
#0	35	0.959	Biodegradation	Biodegradable plastics, bacterial community, low-density polyethylene, microorganisms
#1	31	0.975	Sediments	Quantification, microplastics, pollution, particles
#2	29	0.775	Conventional microplastics	Biodegradable microplastics, eem-parafac, soil-dissolved organic matter, bacterial community structure
#3	29	0.903	Heavy metals	Soil pollution, cadmium, soil organic carbon, metal ions
#4	29	0.890	Antibiotic resistance genes	Polyvinyl aromatic hydrocarbons, sorption, bioaccessibility, phenanthrene
#5	29	0.913	Polyvinyl chloride	Soil fauna, polyethylene terephthalate, food chain, analytical methods
#6	28	0.810	Sewage sludge	Composting, wastewater treatment plants, plastic pollution, soil health
#7	27	0.835	Organic pollutants	Bisphenol a, microplastic pollution, great lakes, antibiotic-resistant genes
#8	26	0.830	Near-infrared spectroscopy	Polyester fibres, DNA damage, soil environment, earthworm
#9	25	0.874	Gut microbiota	Agricultural soil, plastic film, mulch degradation, microbial diversity
#10	25	0.812	Distribution characteristics	Microplastic contamination, pollution characteristics, research trends, medicinal animals
#11	24	0.923	Density separation	Fourier transform infrared spectroscopy, photosynthesis, recycling, marine litter

Clusters #8, #10, and #11 are focused on the distribution characteristics and analytical methods for soil microplastics. Microplastics have been found in soils across all seven continents in diverse environments such as coastlines, farmland, riparian forest buffer zones and cropped areas (Yang et al., 2022). Through a method based on pressurized fluid extraction (PFE), microplastics were detected in 90% of soil samples from an industrial area in Sydney, with concentrations in the range of 300–67,500 mg/kg (Fuller and Gautam, 2016). In Iran and Chile, the microplastic concentrations in farmland soils were 67–400/kg and 600–10,400/kg, respectively (Corradini et al., 2019; Rezaei et al.,

2019). The average abundance of microplastics in farmland soils in southeast Germany was (0.34 ± 0.36) /kg (Piehl et al., 2018). As a major producer and user of plastic products, China's soil is contaminated with microplastics to varying degrees. Microplastics have been found in mulched farmland soils in Shanghai, Liaoning and Shanxi Provinces with abundances as high as 10,586/kg, and the abundance increases with the number of mulching years (Lv et al., 2019; Ding et al., 2020; Li et al., 2022). Huang et al. (2020) investigated microplastics in agricultural soils by analysing 384 soil samples collected from 19 provinces across China. They found that the microplastic concentrations in the soil samples were

0.1–324.5 kg/ha, with an average of 83.6 kg/ha. However, soils is a system with complex composition, and microplastics may interact with soil components such as organic matter, mineral soil and chemical ingredients, posing an adverse effect on the detection of soil microplastics (Zhang et al., 2020). Therefore, while various analytical methods have been developed to study the microplastics in aquatic environments, there is currently no standardised analytical process available for soil microplastics.

Analysing microplastics in soil samples involves extraction, separation, identification and quantification. A method for effectively separating microplastics from soil samples is required. Density separation is commonly used to isolate low-density plastic particles from soil samples, which formed a distinct cluster in the retrieved literature. Sodium chloride (NaCl), which has a density of 1.2 g·cm⁻³, is commonly used to separate less dense particles from environmental media (Thompson et al., 2004). In addition, high-density solutions such as saturated sodium polytungstate can be used to isolate certain high-density microplastics (Corcoran et al., 2009). After separation, microplastics are commonly identified by microscopy, spectroscopy and thermal analysis (Woo et al., 2021). Light microscopy is commonly used for identifying microplastics with large particle sizes, but its reliability and accuracy are poor. Scanning electron microscopy and transmission electron microscopy have also been used for microplastic identification. Fourier transform infrared (FTIR) spectroscopy can be used to easily identify specific chemical bonds and reveal the polymer composition of microplastics. Raman spectroscopy can generate unique spectra for polymers with different molecular structures and atoms, so it provides an efficient way to explore the chemical structure of microplastics (Witzig et al., 2020). Recently, thermal analyses have been utilised to identify microplastics in samples, and they include techniques such as differential scanning calorimetry (DSC, Arhant et al., 2019), thermogravimetric analysis (TGA, Uheida et al., 2020) and pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS, Mizuguchi et al., 2023). Thermal analysis often complemented by other techniques, such as GC-MS, to overcome its limitations (Bitter and Lackner, 2021). New instruments have been applied to improve the efficiency and accuracy of microplastic identification in recent years, and they are sometimes used in combination to compensate for the shortcomings of individual technologies. Erni-Cassola et al. (2017) combined visual classification with fluorescent staining to identify microplastics. Shim et al. (2016) used Nile Red [9-diethylamino-5H-benzo (α) phenoxazine-5-one] to stain microplastics. Atomic force microscopy (AFM) can be combined with infrared and Raman spectroscopy for the analysis of microplastics and even nanoplastics. AFM can achieve nanometer-resolution imaging to reveal the chemical structure of target plastics (Luo et al., 2021a). Near-infrared (NIR) spectroscopy (Paul et al., 2019), vis-NIR spectroscopy (Garaba and Dierssen, 2017) and nano-thermal analysis (Luo et al., 2021b) have all been used for microplastic identification. Overall, analytical methods have been rapidly developed for research on microplastics, but a standardised approach is still lacking. Reliable detection and monitoring methods are urgently needed so that measured data from different sources can be compared.

Clusters #3, #4, and #7 are focused on the composite toxicity of microplastics and other pollutants in soil (e.g., heavy metals,

organic pollutants, ARGs). Due to their small size, strong hydrophobicity and large specific surface area, microplastics have strong adsorption properties and can act as vectors for many contaminants in soil. Microplastics have been measured to have pollutant concentrations hundreds of or even thousands of times higher than that of their surrounding environment (Mato et al., 2001; Hirai et al., 2011). The interactions of microplastics with other contaminants may alter their surface properties, environmental behaviour and toxic effects and thus increase their adverse impact on soil ecosystems (Wang F et al., 2022). Heavy metals are a common soil pollutant and easily interact with microplastics through electrostatic attraction, chemical bonding and binding with oxygen-containing functional groups on their surface. Microplastics can also interact with other hydrophobic organic pollutants such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, petroleum hydrocarbons (PHCs) and organochlorine pesticides (OCPs). ARGs pose a significant risk to human health and have become a major public concern. Microplastics can serve as a host for distinct bacterial communities compared to the surrounding environment and exert selection pressure for the development of ARGs (Liu et al., 2021). In addition, additives (such as plasticizers, flame retardants, photostabilizers, antioxidants, and pigments) are intentionally added into plastics during production to maintain or enhance their properties (Do et al., 2022). Many of these organic additives are hazardous. After entering the soil, microplastics can undergo a series of aging and wear process, and their own additives are gradually released and coexist with microplastics in the soil environment, causing joint pollution to the soil ecosystem. Overall, the risk posed by microplastics combined with coexisting pollutants is still unclear in terms of toxicity and formation and requires further studies.

Cluster #6 is focused on the microplastics from sewage sludge. Microplastics is a common pollutant in wastewater treatment plants (Murphy et al., 2016). Wastewater treatment plants can effectively remove microplastics from wastewater, and over 95% of microplastics in wastewater are removed and concentrated in sewage sludge, which is often applied to fertilize fields as agricultural amendment and soil compost due to its good properties as fertilizer, posing a potential threat for soil health (Li et al., 2018; Berg et al., 2020; Rolsky et al., 2020). According to the review of Blasing and Amelung (2018), the concentrations of plastic detected in sludge ranged from 1,500 to 24,000 items kg⁻¹. The high microplastics load of sewage sludge makes it one of the most important input path of microplastic to soil (Nizzetto et al., 2016). The presence of microplastics in sewage sludge derived from wastewater treatment plants has only been studied to a limited extent. The fate of microplastics in sludge treatments, and the effect of microplastics derived from sludge processes to soil system need to be further studied.

Cluster #9 is focused on the impact of microplastics on gut microbiota. Gut microbiota plays an important role in on host health, metabolism and immunity. In addition, it is closely related to soil decomposition processes. Due to the differences between the microbial gut environment and the surrounding soil, gut microbiota of soil organisms is significantly distinct from that in the surrounding soil (Thakuria et al., 2010). However, research on the effects of microplastics on gut microbiota is in its absolute

TABLE 4 Top-15 keywords with the strongest citation bursts in soil microplastics research.

Keywords	Strength	Begin	End	2016–2023
Litter	8.21	2016	2020	
Ingestion	7.21	2016	2019	
Size	2.49	2016	2018	
Debris	7.95	2017	2020	
Extraction	4.76	2017	2020	
Lumbricus terrestris	3.15	2017	2018	
Metabolism	2.79	2017	2019	
Sediment	2.79	2017	2019	
Synthetic fibres	13.33	2018	2020	
Persistent organic pollutants	4.67	2018	2019	
Environmental samples	2.58	2018	2020	
Abundance	6.38	2019	2021	
Knowledge gaps	7.32	2020	2021	
Dissolved organic matter	3.01	2020	2021	
Deposition	3.68	2021	2023	

infancy. As an exogenous soil pollutant, microplastics can generally induce gut microbiota dysbiosis in terrestrial organisms. For example, studies on the effects of microplastics on the gut microbiota of soil organisms have shown that microplastics could induce gut microbiota dysbiosis in collembolan *Folsomia candida* (Zhu et al., 2018), *Tenebrio molitor* larvae (Urbanek et al., 2020), mice (Jin et al., 2019), and soil oligochaete *Enchytraeus crypticus* (Zhu et al., 2018). In contrast, Wang et al. (2019) reported that microplastics exposure has little effect on the gut bacterial communities of earthworms *Metaphire californica*. Different types, sizes, shapes, additives, as well as exposure concentration and time of microplastics may influence the effects of microplastics on the gut microbiota of soil organisms, which should be investigated systematically.

3.5 Hotspots and emerging trends of soil microplastics research

Burst detection is used for monitoring transitions in the research fronts of a field. Table 4 lists the top-15 keywords in terms of burst strength and duration. The red line shows when a keyword was most frequently cited.

Keywords such as “litter,” “ingestion” and “extraction” had burst durations of more than 4 years, which indicates that these topics have always intrigued researchers and have been extensively studied. Between 2016 and 2020, the keyword “litter” had a burst strength of 8.21, which indicates continued concern about the possible threat of microplastics to terrestrial ecosystems and humans. The keyword “ingestion” appeared between 2016 and 2019, indicating concerns about the exposure of organisms, particularly humans, to microplastics through ingestion. Humans can ingest microplastic particles through ingestion, inhalation or skin contact. Cox et al. (2019) suggested that people might ingest 39,000–52,000 microplastic particles annually through food. Microplastics can also enter the human body through the food chain. The keyword “extraction” is an essential analytical procedure for soil microplastics, and it indicates concern over the development of analytical methods. The keyword “synthetic fibers” showed the highest burst strength of 13.33. Synthetic fibres can be considered as a type of microplastics, which can be shed from synthetic fabrics during conventional washing of synthetic fiber clothes, as well as falling out in indoor environments (Falco et al., 2019; Zhang et al., 2020). Nowadays, synthetic fibres have been found in various environmental media, and the additives and dyes contained in synthetic fibres are hazardous to wildlife and humans (Velasco

et al., 2022), which have posed widespread concern. In addition, the keywords “abundance” and “persistent organic pollutants” also demonstrated relatively high burst strength. The keyword “abundance” suggests concern over the abundance of microplastics in soil found in different regions of the seven continents (Zhang and Liu, 2018; Zhou et al., 2018; Yang et al., 2022). The keyword “persistent organic pollutants” indicates concern over the interactions between microplastics and persistent organic pollutants.

We defined the latest research front as keywords that emerged from 2020 to 2023, which included “dissolved organic matter,” “deposition” and “knowledge gaps”. The keyword “dissolved organic matter” indicates interest in the role of dissolved organic matter in the fate and transport of microplastics (Cao et al., 2023). The keyword “deposition” indicates concern over microplastics suspended in the atmosphere that can settle on soil surfaces through air transport (Cai et al., 2017; Liu et al., 2019). The keyword “knowledge gaps” indicates an awareness that research on soil microplastics is immature and requires further development. Sampling, extraction, separation, identification and quantification procedures should be standardised. In addition, research is still lacking on the mechanism by which microplastics influence soil properties and their direct or indirect toxicity on plants, fauna, microorganisms and humans. The adsorption mechanism and consequences of microplastics as pollutant vectors should also be further investigated (Rocha-Santos and Duarte, 2015).

4 Discussion

Microplastics have been found in diverse soil types across continents. However, compared with marine and freshwater ecosystems, the soil matrix is complex with numerous factors; hence, research on soil microplastics is still in progress. Accurate monitoring, including extraction, separation, identification and quantification, is essential for improved understanding of soil microplastics. Improved technologies with high sensitivity and precision have been utilised to detect soil microplastics, but assessment methods are still in the developmental phase. Moreover, the absence of standardised procedures for sampling, pre-treatment and quantification of microplastics has impeded the comparison of microplastic pollution across different regions. Soils have complex compositions with diverse pollutants, such as heavy metals, organic pollutants and ARGs, with which microplastics interact readily. The combined effects on soil environment and organisms are also of concern. Researchers have made significant efforts to explore the impact of microplastics on soil biota and health, and much progress has been made in understanding their toxic effects on soil fauna, plants and microorganisms, as well as their direct influence on the physicochemical properties and material circulation of soil. However, research on the mechanism by which microplastics interact with the soil matrix is still in the preliminary stage. Most studies on the toxic effects of microplastics on soil biota have been conducted in laboratories; hence, they do not accurately reflect real-world environments. Microplastics can affect the digestive, respiratory, reproductive and cardiovascular systems of humans through ingestion, inhalation or skin contact. However, research on microplastics has predominantly been conducted on

animals, and further studies are needed to explore their effects on humans.

We conducted a bibliometric analysis to clarify the research progress, hotspots and developing trends of soil microplastics. Research on soil microplastics can be divided into two stages. In the slow development stage (2016–2018), researchers noticed the potential harm caused by microplastics in soil and focused on determination methods and their occurrence and accumulation in soil. In the rapid development stage (2019–2023), growing concern on soil microplastics led to diversified research directions that considered their fate, exposure toxicity, adsorption, biodegradation and bioaccumulation. Cluster analysis identified 12 clusters of research on soil microplastics, including biodegradable microplastics, the distribution and analytical methods, the composite toxicity of microplastics with other pollutants and their effect on soil microorganisms. Burst detection indicated that research on soil microplastics has continued to focus on the development of analytical procedures and possible threats to terrestrial ecosystems and humans. Moreover, many knowledge gaps that remain unaddressed in this field are gaining attention in recent times.

We suggest that future research on soil microplastics should focus on the following aspects:

- Develop a standardised analytical procedure and unit for measuring the concentration of microplastics in the soil (e.g., by quantity or weight) and systematically monitor their distribution in soils with different land uses and from different regions.
- Examine the relationship between microplastics and biochemical processes in the soil to clarify the mechanism by which they affect soil properties and their direct or indirect toxicity while they move through the food chain.
- In addition to laboratory-based studies, conduct field trials with doses close to realistic levels in the environment to analyse the potential risks and propose environmental management and restoration strategies.
- Collect more information on how microplastics combine with other environmental pollutants and their toxicological effects on soil biota and health.
- Explore separation and extraction standards for biodegradable microplastics; their environmental behaviour and ecological effects; their impact on microorganisms, fauna and plants; and the adsorption and desorption of toxic substances from biodegradable microplastics as well as investigate the feasibility of using them for sustainable development.

Plastics are necessary to current lifestyles. Instead of banning the use of plastic products, sustainable strategies are required to reduce the microplastic contents in soil. For example, legislation should be proposed to strengthen the control over the use of non-degradable plastics and related products and to increase public awareness for sorting household garbage. More efficient technologies and tighter technical standards should be proposed to improve the recycling rate of plastic waste, providing more theoretical and practical support for plastic waste control.

Bibliometric methods based on CiteSpace can clarify the research context of a certain field. However, compared with

traditional reviews, CiteSpace has its limitations. For example, Citespace software is time-consuming and laborious on merging synonyms, which have to be combined manually. In addition, Citespace is presented in a literature statistical manner and lacks the of experimental study support, which may obscure the information of the research itself. In future studies, the combination of bibliometric analysis and other analyses (such as model analysis) may be an effective way to make the results more realistic. Moreover, we should note that while there is no significantly impact on the main conclusions of the work, it is undeniable that some detailed information, such as the quantity, weight and size of microplastics, was omitted when using Citespace for literature analysis. In the future, the combination of Citespace and pluralistic text analysis methods, such as word frequency analysis, entity recognition, relationship analysis, etc., is expected to enrich the discussion of detailed information. We also look forward to developing new software on the basis of citespace to further embed these text screening functions.

Author contributions

JM: Conceptualization, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. WH: Methodology, Software, Visualization, Writing–original draft. RP:

Validation, Writing–review and editing. KZ: Conceptualization, Supervision, Validation, Writing–review and editing.

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Author WH was employed by Inspur Software Group Ltd.

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