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Review and future trends of soil microplastics research: visual analysis based on Citespace

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Abstract

Compared with the research results of water microplastics, soil microplastics have been of concern for a shorter time, and the research started later. As a whole, they are still in the initial stage of development, and the problems of arable land and food security caused by them have attracted close attention from scholars around the world, but have not been effectively solved. To reveal the research status, development and change process and future trend, this paper is based on the data in the Web of Science (WOS) databases from 2016 to November 2021, with the help of Citespace software. The number of articles published, source countries and degree of cooperation, research institutions and teams, keyword clustering and change trend are sorted out. The results showed that: (1) the research results of soil microplastics has experienced a slow-rapid growth stage. In terms of the number of articles published, China occupies the first place in the world, with 55 articles. In terms of the number of publications, Free Univ Berlin ranks first, followed by the Chinese Academy of Sciences, Berlin Brandenburg Inst Adv Biodivers Res, and Wageningen Univ&Res. (2) In terms of content, environmental pollution and exposure, the function and health of soil-associated media, the common shape characteristics of microplastics and their influencing factors, and the combined pollution caused by microplastics are all covered, and can be divided into eight main categories: soil, ingestion, heavy meals, fiber, marine environment, microplastic, metals, and plants. (3) The migration behavior and ecotoxicological effects of microplastics in soil media are still the focus of attention at present. (4) In the future, "regression process and mechanism", "detection method and evaluation standard", "risk assessment model", "removal technology and control means" are undoubtedly worthy of attention.

Keywords: Cluster mapping, Ecotoxicological effects, Carrier band stabilization, Risk assessment models, Citeseace, Soil microplastics

Introduction

Microplastics, a general term for plastic debris and particles with a particle size of less than 5 mm [1], have attracted much attention because of their strong adsorption [2] and their ability to cause continuous compound pollution [3] to the environment. In recent years, microplastics have been detected in the ocean [4], surface rivers and lakes [5], food [6, 7], the atmosphere [8], soil [9, 10] and even in the rarely visited polar regions [11] and deserts [12]. This shows that microplastic pollution has gradually developed into an urgent environmental and health problem for human beings.

As far as the environmental medium is concerned, the research on microplastics starts from the water body, and then transitions to the soil and atmospheric systems, but the research on microplastics in water is still in a leading position. In 2004, British scientist Thompson [13] published a paper in the journal Science on plastic debris in marine water and sediments,

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proposing the concept of "microplastics" for the first time. Subsequently, traces of microplastics were found in the Mediterranean Sea [14], the North Pacific [15], the North Atlantic Ocean [15], the South China Sea [16], and the Yangtze River Basin [17]. In 2012, German scientist Rilling [18] published the article "Microplastic in Terrestrial Ecosystems and the Soil" in the journal Environmental Science and Technology, which was the first report on microplastics in soil. After that, micro (nano) plastics were successively detected in the atmosphere and food. In terms of research content, microplastics research has undergone a transition from detection in environmental media [19, 20] to toxicity evaluation of microplastics [21, 22] to the current research of the environmental behaviour of microplastics [23]. However, compared with water bodies, the overall research on microplastics in soil is still in the early stage of rapid growth. Most of the researches focus on the pollution status of microplastics in soil [24] and how to identify and extract microplastics from soil quickly and efficiently [25, 26]. A review of existing methods for the analysis of microplastics in soil matrices has also been conducted and it was found that there is still no suitable method that can handle the analysis of smaller microplastics [27]. Therefore, how to establish a standardized microplastic analysis method for soil matrices needs to be further explored. Other studies have shown [28] that microplastics are composed of carbon and other elements. This determines that when microplastics enter the soil, they can have a significant impact on soil structure, plant growth and most likely affect the stability of soil aggregates to alter erosion rates. However, the mechanisms of microplastic action in soil are not yet systematically studied, especially the migration behaviour of microplastics needs to be further sorted out and summarised. This will facilitate the indexing and searching of relevant research information and thus promote the study of soil microplastic systems. In this paper, Web of science (WOS) was used as data sources to search the relevant literature in the field of soil microplastics from 2016 to 2021 at domestic and international level. Through the econometric analysis of the number of publications, major publishing countries and degree of cooperation, research institutions and teams, keyword clustering and changing trends, we clarify the outstanding teams in the field of soil microplastics, provide ideas for researchers who are just starting out, and summarize the hot spots and research directions of concern in the field of soil microplastics at the present stage. Furthermore, based on the available literature, an attempt was made to summarise the gaps in the current research in the field of soil microplastics, with a view to providing a theoretical basis for research related to microplastics in soil, as well as a reference direction for understanding future research developments in this field.

Data resource

The data of this study were retrieved from WOS with the keywords "Microplastic" + "soil". The retrieved papers were published from 2016 to November 2021 and the search was conducted on 17 November 2021. And a total of 159 papers were searched as the base material for the analysis of this paper. 159 documents were exported from the WOS database in plain text format, with "Full Record and Cited References" in the bibliographic record as the source data to be processed. In addition, with the help of Citespace software (Version 5.6.R2, Citespace is able to present the evolution of a field of knowledge in a single citation network map. This can be used by scholars who are just starting to explore a field by showing the focus of attention on the field in different countries in different years in as many ways as needed.), the time span was set to January 2016–November 2021, the time partition was 1 year, and the node types were selected as country, author, institution, and keyword. The cropping method was also selected as pathfinder, pruning sliced networks. The rest of the settings were left as default, and the software was run and co-occurrence and clustering analyses were performed. It is worth noting that since there were basically no results on soil microplastics published before 2015, the data retrieval started in 2016.

Result analysis

Annual analysis of publications

The number of publications in the field of soil microplastics is shown in Fig. 1. Among them, the data retrieved by WOS showed that soil microplastics research has experienced a slow initial stage and a rapid development stage with a surge in publications. Among them, from 2016 to 2017, 2–3 articles were published on average, which can be classified as the initial stage of slow development; from 2018 to 2021, the number of published papers increased rapidly in an exponential form, and even reached more than 50 papers in 2021. The research on soil microplastics has initially entered a stage of rapid growth.

In addition to the rapid growth of soil microplastics publications, the scientific influence of its research results is gradually emerging. In particular, several representative scientific research results with high citation frequency appeared around 2018, and these results mostly focused on the potential damage to soil ecosystems. For example, Alice A Horton [29] published a research paper, arguing that the ecological impact of microplastics on the aquatic environment can be applied to the terrestrial environment, and put forward the research focus of

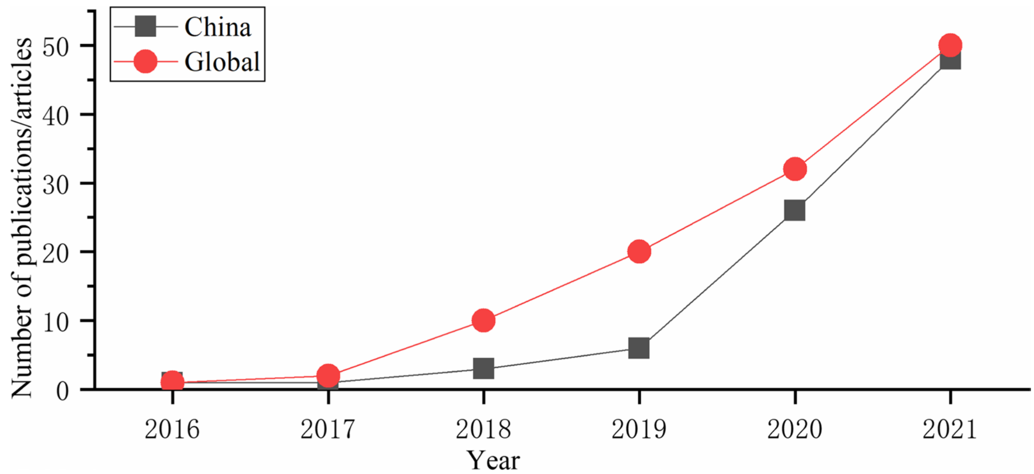

Fig. 1 Quantity of publications on microplastic in soil environmental field from 2016 to 2021

future terrestrial systems, pointing out the direction for later scholars who study terrestrial microplastics, and the results have been cited 742 times. Machado A A D [30] and Ng E L [31] sorted out the potential hazards of microplastics to ecosystems in two dimensions: terrestrial systems and agricultural systems, respectively. And Blasing M [32] discussed that the main way for microplastics to enter the soil may be wastewater Irrigation. Another scholar, He D F [33], conducted a more comprehensive study of soil microplastics. This involved a number of key scientific issues ranging from analytical methods, pollution characterisation to ecological risks, and provided new theoretical support for the prevention and control of microplastic pollution in terrestrial ecosystems. More importantly, the papers are all cited between 200 and 400 times. In addition, the influence of some soil microplastics research results published in 2020–2021 is gradually emerging over time [34–36].

To show the status of microplastic publications in Chinese journals, this paper searched the papers in CNKI (the search time and content were the same as that of WOS) with "microplastic" + "soil" as the subject term, and obtained 84 papers in total. The volume of published papers in the field of soil microplastics included in CNKI has generally experienced three stages of development between 2016 and 2021: early stage, slow growth stage and fast growth stage. In the initial stage from 2016 to 2017, only 1 article was published per year, and the focus was on the separation and extraction methods of microplastics in soil [37, 38]. The period from 2018 to 2019 was the slow growth stage of domestic soil microplastics. As can be seen from the keywords of the retrieved literature, domestic scholars began to explore the environmental behavior of soil microplastics. For example, Ren Xinwei [39] studied the ecological effects of soil microplastics. Zhang Simeng [40] investigated the impact on human health by summarizing the transport behaviour and sources of microplastics in the environment. After 2019, the number of publications increased rapidly, and microplastics began to be linked to small soil animals [41], such as microorganisms [42], plants [43], and earthworms, other soil pollutants [44], and even carbon emissions [45], and the research direction was diversified.

In summary, scholarly interest in soil microplastics continues to grow and involves a variety of aspects. This indicates that soil media is beginning to emerge as a hot spot in the field of microplastics.

Publishing countries and their international partnerships

To obtain the information on the number of published articles in the field of soil microplastics in various countries in the world, this paper extracted the country and region information of published articles with the help

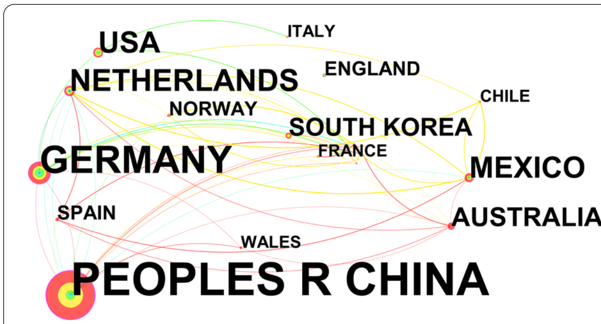

Fig. 2 Co-occurrence map of source countries in soil microplastics field in WOS (Citespace software uses the diameter of the circle to indicate the amount of posts in the result presentation. The larger the diameter, the more the number of posts..)

Fig. 3 Network of cooperative relationships between published countries in WOS

of Citespace software (Figs. 2, 3). As can be seen from Figs. 2, 3, the country with the largest number of publications on soil microplastics research from 2016 to 2021 is China, with a total of 55 publications. This is due to the fact that China has always attached great importance to soil quality and people's life and health, especially in recent years, the Chinese government has successively promulgated the "Soil Pollution Prevention and Control Action Plan", "Soil Environmental Quality Agricultural Land Soil Pollution Risk Control Standard (Trial) (GB15618-2018) " and a series of laws and regulations, and carried out soil quality surveys across the country to build high-standard farmland [46]. On the other hand, with the rapid development of science and technology and economy, China is playing an increasingly leading role in various global environmental problems facing mankind. In addition, the Chinese government is highly concerned about new pollutants [47, 48] and actively encourages universities and research institutions to focus on research in the field of soil microplastics (35 Chinese universities and research institutions are involved in this WOS data). For example, China is a large country in terms of plastic mulch (one of the main sources of soil microplastics), with the world's largest area covered by plastic mulch for agriculture. If a country has a high demand for plastic mulch, the investment in research in this area will also increase proportionally [49], and therefore, its research results will naturally be higher in number. Germany, with 25 articles, in second position. Germany is at the forefront of environmental technology in the world. As part of the government's policy to combat microplastic pollution (plastic restriction, introduced in 2016), the German manufacturer Rauschmann has created the world's first "microplastic-free" certified personal toiletries. It is clear that national policies can influence the proportion of research institutions and companies that devote themselves to this area of research, and that the number of publications naturally increases. Other countries such as the Netherlands (12 papers), the United States (11 papers), Mexico (11 papers), and Australia (8 papers) have published more than 8 papers in the field of soil microplastics and are part of countries with more scientific attention and publications in this field.

Of course, there are certain connections between countries in the field of soil microplastics research, and the closeness of the connection is indicated by the thickness of the connection (Fig. 3). As can be seen from Fig. 3, China is not only the country with the largest number of publications, but also the country with the highest intensity of international cooperation. It cooperates closely with Canada, New Zealand, Turkey and other countries, indicating that China has gradually paid more attention to the field of soil microplastics in recent years. It is reflected in: (1) China supports various types of countries to send overseas students to study abroad, and to learn advanced technologies from other countries while sending talents to the outside world. (2) China attaches great importance to an open communication attitude in the field of science and technology, and actively establishes friendly exchanges and cooperation with other countries in the world, making China's contribution to scientific and technological progress. Germany and the Netherlands also have more international exchanges in the field of soil microplastics, and both have cooperation and exchanges with China, Australia and Finland. The difference is that Germany has closer ties with developed countries and the Netherlands has closer ties with developing countries, which may be related to German and Netherlands study abroad policies. It is worth mentioning that the Netherlands is a pioneer in soil remediation, focusing more on the load of microplastic pollution on the soil, and many developing countries are willing to learn from the Netherlands experience, so they all have cooperation relations with the Netherlands. It is interesting to note that the United States, one of the most developed countries in the world, does not have the same level of cooperation with other countries in the field of soil microplastics as Mexico as far as the intensity of cooperation is concerned. This may be related to the large number of scholars and the intense clash of ideas within the United States. Mexico, on the other hand, is a developing country, but it has a long history of culture and a focus on international exchange and cooperation. Australia cooperates and exchanges more closely with European Union (EU) countries, such as Sweden, the Netherlands and Spain. In addition, the EU has published "the Soil Environment Monitoring and Evaluation Project", "the Soil Strategy 2030" and other regulations on the protection of the soil environment, driven by common goals, the EU countries are also more closely linked in soil health.

Publishing institutions and research teams

Based on the information extracted from the Citespace software, it is possible to focus on the current global teams working on soil microplastics and their main focus and scientific contributions, as shown in Fig. 4. It can be seen that the institution with the largest number of publications is Free Univ Berlin, with a total of 14 publications.

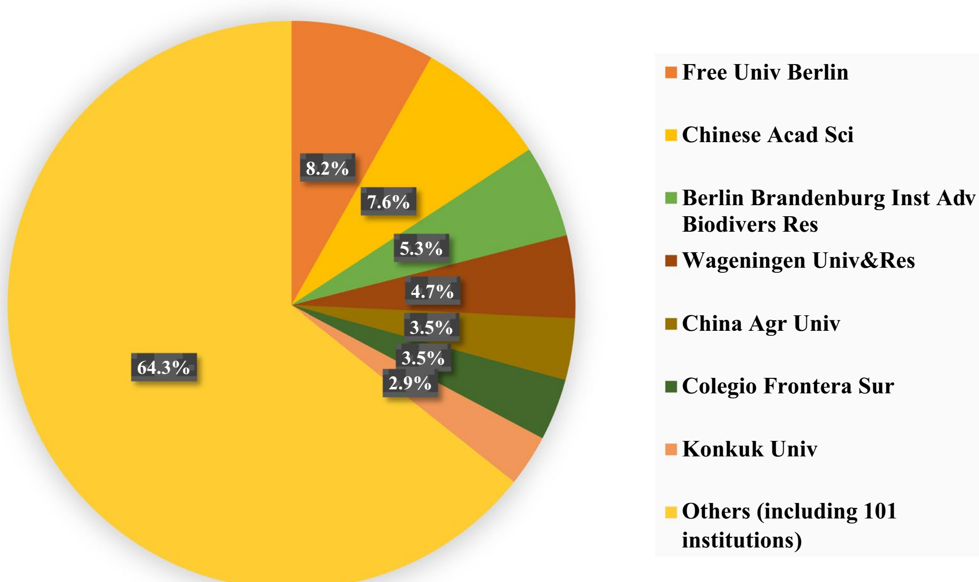

Fig. 4 Map of soil microplastics in WOS

Among them, the Machado A A D team has two research articles on soil microplastics that have been cited more than 130 times. Machado A A D team made outstanding contributions in the direction of soil properties and soil ecosystem impacts caused by microplastics [50–53]: in terrestrial systems, microplastics may interact with organisms first, and microplastic particles with different particle sizes have different effects on the physical and chemical properties of soil. Furthermore, microplastics can also affect the pathways of plant growth mechanisms, potentially altering plant community composition in the future [54].

The contribution of the Chinese Academy of Sciences in the field of soil microplastics ranks second, with a total of 12 papers published. Among them, the Luo Yongming team of Nanjing Soil Research Institute has contributed a lot. The team has been engaged in the research of soil chemistry, soil remediation, regional soil environmental quality, sludge soil utilization and risk management for a long time, and is at the forefront of soil pollution. The research direction is novel and advanced. There have been many studies on soil microplastic pollution and control [55, 56]. For example, there is a huge discovery in how microplastics enter fruits and vegetables through soil media: microplastics can be absorbed by crops and enter their edible parts [57]. This important discovery was highly affirmed by Matthias C Rillig, a famous German soil ecologist. It is worth affirming that Berlin Brandenburg Inst Adv Biodivers Res (5.26%), Wageningen Univ&Res (4.68%), China Agricultural University (3.51%), Colegio Frontera Sur (3.51%), which also have more outstanding research results, are important contributors to international research in the field of soil microplastics.

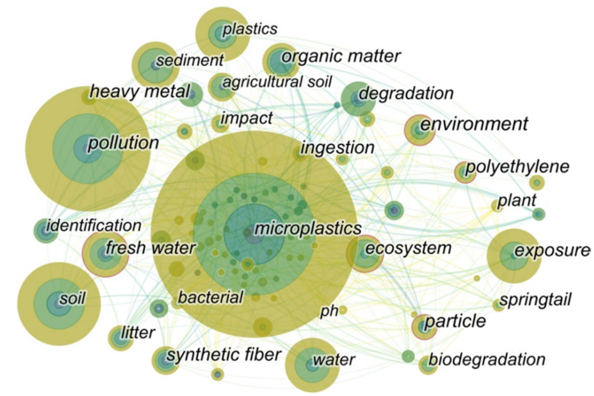

Fig. 5 Distribution of keywords in the field of soil microplastics in WOS

Table 1 Co-occurrence keywords in soil microplastics in international journals[a]

Number	Keyword	Centrality	Word frequency
1	Microplastics	0.3	62
2	Pollution	0.13	36
3	Soil	0.09	26
4	Plastics	0.11	18
5	Exposure	0.07	17
6	Water	0.06	16
7	Sediment	0.02	15
8	Fresh water	0.16	14
9	Ecosystem	0.25	13
10	Organic matter	0.14	12
11	Degradation	0.18	11
12	Litter	0.06	10
13	Environment	0.07	10

[a] Only summarize keywords with a word frequency of not less than 10 times

Keyword knowledge graph

Keyword co-occurrence knowledge graph

Keyword is a high-level summary of the content of the article, which can reflect the research hotspot and focus of a certain field. Therefore, the development trend of this field can be analyzed according to the time and frequency of the appearance of keywords [58]. Based on the Citespace software, the keywords of 159 documents in international journals were extracted, and the co-occurrence chart of soil microplastic keywords as well as the word frequency and centrality of the corresponding keywords, were obtained, as shown in Fig. 5 and Table 1, respectively. As can be seen from Table 1, "microplastics" appeared 62 times as a keyword in 159 retrieved articles, with the maximum centrality, indicating that soil health remains a hot topic, of these, microplastics are the key node of soil microplastics field keywords and the connection point of other keywords. And the keyword "pollution" appeared second in frequency (36 times), indicating that the import of microplastics and soil pollution are important focuses of attention. The remaining keywords are closely related to soil microplastics, and can be roughly classified into the following four categories according to their associated content.

(1) Environmental pollution and exposure routes. In Fig. 5, the greater the radius of the node, the greater the frequency of co-occurrence of the corresponding keyword. Therefore, it can be concluded that the most researches on soil microplastics are pollution, exposure, degradation, environment, biodegradation and other keywords from Fig. 5. This indicates

that the most attention in this field is the environmental pollution, exposure routes and sources and sinks processes of microplastics. Microplastics have a negative impact on plants and animals in the terrestrial environment [59, 60] and can accumulate in the soil and have a persistent effect on soil ecosystems [61] (environmental pollution of the environment will be mentioned in detail in subsequent chapters). At the same time, it has been found that microplastics can be transferred with natural nutrient chains on one hand, e.g., crops such as wheat, lettuce and broad beans can absorb and accumulate microplastics [62–65], which eventually enter the human body by means of food and drinking water. On the other hand microplastics floating in the air can enter the body with the respiratory tract [66]. It is worth noting that humans can also come into direct dermal contact [67] with microplastics present in detergents and personal care products. And microplastics are already present in human stool [68], blood and placenta [69] and can cause inflammation and stress in humans in severe cases [70].

(2) The soil is related to the function and health of the media itself. Keywords such as soil, agricultural soil, ecosystem, water, freshwater, sediments, plants, and springtails appear in the co-occurrence map of soil microplastics keywords, indicating that the field of soil microplastics is not only concerned on the pollution and exposure of soil or farmland media [71], but also great importance is attached to the study of the function and health of various water bodies and their sediments, vegetation, bacteria, microorganisms or small soil animals associated with soil microplastics.

(3) The common shape characteristics of microplastics and their influencing factors. Keywords such as garbage, synthetic fibers, particles, pH, organic matter, etc., indicate that these are the shape characteristics and influencing factors of microplastics that are often concerned. In terms of sources, some plastic wastes are weathered and broken up to increase the abundance of microplastics in soil [72]; in terms of shape characteristics, fibrous and granular microplastics are widely present in soil, and special attention is paid to fibrous microplastics in farmland soil. Degradation of plastics from human beings (synthetic fiber clothes) and brought into soil by agricultural tools during long-term agricultural activities [73]; in terms of influencing factors, changes in pH and the content of organic matter in the environment can affect the adsorption capacity of microplastics [74].

(4) Associated pollution caused by microplastics. Other pollutants such as heavy metals are often associated with the adsorption–desorption behavior of microplastics. A large number of studies have shown [75–77] that microplastics have adsorption effects on heavy metals Zn^+, Cu^+, Hg^+, Cd^+, Pd^+ and so on. These heavy metals are enriched on the surface of microplastics and migrate with them, coexisting with persistent organic pollutants such as polycyclic aromatic hydrocarbons adsorbed by microplastics. If the pH and temperature in the environment change, desorption will occur, and heavy metal particles and persistent organic compounds will be "released" into the environment, changing the physical and chemical properties of the environment, and ultimately having a joint impact on the environment.

Keyword clustering map

To further analyze the correlation between keywords, cluster analysis was performed on the keywords based on the co-occurrence of keywords. Among them, Q value = 0.4968 (> 0.3), S value = 0.7705 (> 0.7), indicating that the clustering structure is significant and the clustering results are more convincing. The specific clustering is shown in Fig. 6. In Fig. 6, each polygonal color block represents a cluster, the keyword on the color block is the label of the corresponding cluster. The smaller the number on the label, the larger the cluster size, and the more important the cluster is. The keyword clustering map shows that the soil microplastic keyword clusters in this study are divided into eight categories in descending order of cluster size: soil, ingestion, heavy metals, fibers, marine environment, microplastic, metals, and plants. Among them, the keywords of ecosystem, fungi, biodegradation, and adsorption belong to the first cluster, namely, the soil category (Fig. 6). This shows that the interaction and biological effects of microplastics and microbial communities in soil is one of the research hotspots in the field of soil microplastics. For example, Chai [78] found that bacteria attached to microplastics have the ability to degrade pollutants, such as heavy metals and toxic compounds, when they studied the soil in Guiyu; Rillig M C [79] also found that plastics are transported into the soil and microplastics are passed along the soil food chain. The second largest cluster is ingestion, which includes keywords, such as earthworm, pollution, and exposure (Fig. 6). Some studies have found [80] that earthworms can carry microplastics from the soil surface down to the soil profile, and finally It may reach the groundwater layer and affect it, which provides a theoretical

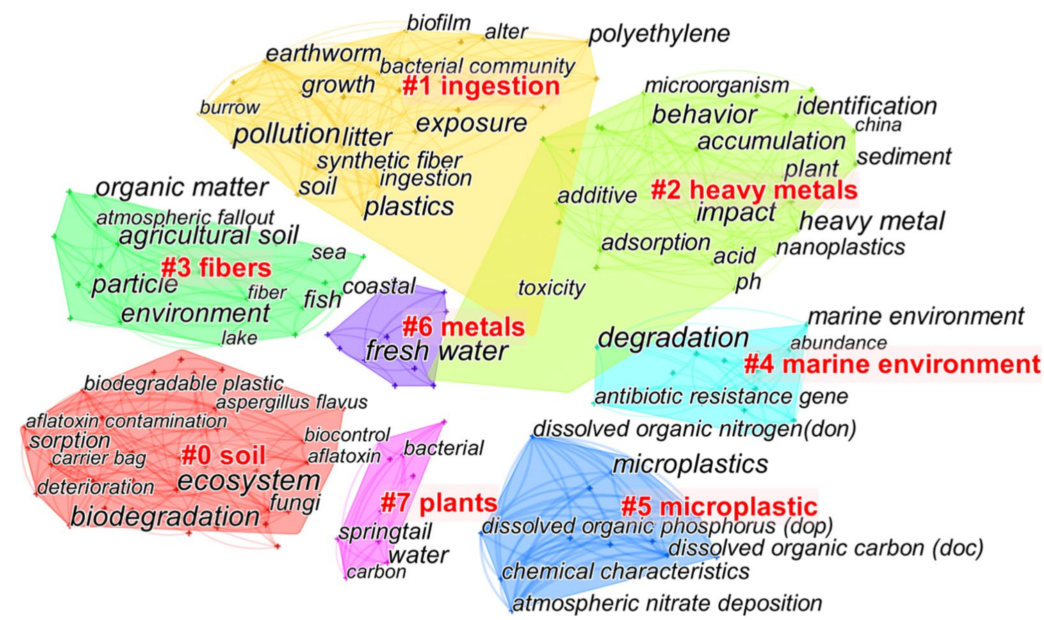

Fig. 6 Keywords cluster atlas of soil microplastics in WOS

basis for the migration of microplastics in the soil to the groundwater environment. Therefore, it can be seen that the migration behavior of microplastics in the soil is also one of the key research directions in this field in the future. The third major cluster is the heavy metals category, and this category is mainly related to accumulation, adsorption, toxicity and impact (Fig. 6). It shows that many scholars are also concerned about the toxic effects of microplastics on the environment based on also exploring the migration behaviour of soil microplastics, especially the intervention of microplastics is likely to produce compound pollution behaviour with soil heavy metals, which in turn increases the uncertainty and complexity of soil pollution. Chinese scholar Hu Tingting [81], who noted that the migration behaviour of microplastics in soil is influenced by their own physicochemical properties, and that ageing microplastics can accelerate the release of endogenous pollutants. And some scholars [82, 83] have even focused on the reproductive toxicity of microplastics: exposure to microplastics can affect the viability of body cavity cells and cause damage to the male reproductive organs. Other clusters such as fiber, marine environment, metals, and plants are all related to the aqueous environment (Fig. 6), suggesting that microplastics can migrate from the soil environment to the aqueous environment, and most scholars [84–87] have suggested that microplastics in the aqueous environment come from (1) surface runoff and subsurface (2) vertical transport by earthworms to groundwater. The clustering of microplastic classes, mostly associated with chemical characteristics, suggests that soil microplastics can cause changes in the physicochemical properties of soils: they can directly affect the density of soils and their ability to retain water [88].

The focus of current research in the field of soil microplastics

Combined with the hotspot clustering in the field of soil microplastics (Fig. 6), the research priorities in the field of soil microplastics from 2016 to 2021 are summarized as follows.

Migration behavior of microplastics in soil media

Soil microplastics achieve vertical and horizontal migration in soil media through wind, hydraulic, plants, small soil animals, and human activities.

Microplastics are moved by wind to different soil surfaces and are then transported vertically by runoff, soil animals, plant root growth [89], and human farming activities [53]. And rainwater runoff can increase soil porosity and make soil surface microplastics infiltrate into the soil with rainwater. For example, Liu F [90] found that in cities, worn tires left on the road surface can enter the surrounding soil through rainwater; while the organisms in the soil (such as earthworms and amoeba) use their own behavioral trajectories to bring the microplastics on the soil surface to the deep soil layer. Lwanga E H

[91] verified that earthworms enhanced the transport of microplastics from the surface layer to the deep soil layer, and proved that earthworms carry microplastic particles are transported downward in the form of digging holes; in addition, plants on land will develop more and more root systems over time, especially arbor plants, whose roots can reach several meters or even tens of meters. If the microplastic particles are attached to the root system when the soil is turned up, it will extend downward with the root system; in spring, when humans turn soil, the microplastic particles on the surface will be turned to the shallow soil area, such as plastic film (which can have a thermal insulation effect on crops in winter) after being weathered or aged, the debris will enter the soil [92].

On the other hand, microplastics that cover the soil surface can also be transported horizontally by soil animals. For example, earthworms and digging mammals such as gophers and moles [93] carry them into burrows through the act of digging, dispersing and transferring microplastics.

In summary, the migration behaviour of microplastics in the soil medium is dominated by vertical migration and supplemented by horizontal migration.

Ecotoxicological effects of microplastics in soil media

The ecotoxicological effects of microplastics in soil media are mainly reflected in the composite superimposed toxicity of other pollutants carried by microplastics and microplastics themselves on soil animals, soil microorganisms and plants.

Effects of microplastics on soil animals The toxicological effects of microplastics on soil animals are mainly carried out by earthworms, and most of them are carried out in the laboratory. To observe the effects of different concentrations of microplastics on earthworms, scholars have conducted relevant exposure experiments. It was found that exposure to dry soil containing 0.2–1.2% microplastics increased mortality and decreased growth rate [94], while exposure to concentrations of 1–20% increased lipid peroxidation in earthworms and caused tissue damage [95]. It is important to note here that the researchers considered the concentrations of 0.2%, 0.4%, 0.5% and 1.2% as environmentally relevant and controlled the experimental temperature at around 20 °C and used a constant soil moisture level of 20%. It can be seen that the higher the concentration of microplastics, the larger the volume eaten by earthworms, but the body weight of earthworms decreases significantly, because high concentrations of microplastics will change the microbiota in the intestinal tract of earthworms [96], and have toxic effects on earthworms, thereby affecting terrestrial ecology system.

Effects of microplastics on soil microorganisms The effects of microplastics on soil microorganisms are mainly manifested in: affecting the composition of microbial communities [97, 98] and changing the activities of soil enzymes [99]. Soil enzymes have high catalytic activity and can indicate soil fertility status, but their activities are often greatly affected by the environment. Microplastics can alter enzymatic activity by changing pH in the soil, and at the same time, microplastics can also affect soil porosity and moisture, leading to a decrease in the mobility of oxygen in the soil, thereby altering the relative distribution of anaerobic and aerobic microorganisms [87]. In particular, it has the greatest impact on the microbial community distributed around plant roots. Changes in enzymatic activity and microbial community abundance can both lead to decreased soil fertility, affecting soil quality and, in turn, plant growth.

Effects of microplastics on soil plants Microplastics not only indirectly affect the growth of plants by affecting soil animals and soil microorganisms, but also directly affect plant roots [56]. In the early research on soil microplastics, some scholars [100] found that microplastics had an inhibitory effect on seed germination and that the larger the particle size of the microplastic within 8–24 h of seed germination, the more detrimental it was to seed germination, which may be caused by physical blockage of the seed stomata by the microplastic particles. In addition, microplastics such as polystyrene can also be absorbed and enriched in the roots of crops, causing changes in the total plant biomass, tissue element composition, and root traits [10].

In short, the ecological effects of microplastics in the soil will all act on the terrestrial ecosystem, and ultimately endanger human health [33, 101]. Therefore, in-depth study of the ecological effects and impact mechanisms of microplastics in soil media is one of the important prerequisites for preventing serious microplastic pollution.

The key direction and development trend of soil microplastics research in the future

(1) In-depth study on the mechanism of microplastics migration behavior in soil media
At present, the research on the migration behavior of microplastics in soil media is not comprehensive enough [85, 102, 103], and there is a lack of in-depth interpretation of the migration mechanism, and further exploration of the mechanism of microplastic carrier migration containing other pollutants is

needed [104]. On this basis, tracking the migration time of microplastics in different soil depths by isotope tracing method is also a way of studying the migration behavior of microplastics in soil media in the future.

(2) Strengthen research on soil microplastic pollution removal technology

Generally speaking, the soil environment is more complex than the water environment [27], with more organic matter (straw, plant residues) in the soil, and the soil surface on both sides of the road is easily covered by impurities, such as dust and asphalt. Efficient removal or separation of microplastics from complex soil environments is a key step in studying the abundance, distribution and sources of microplastics in soil, but there is no fully mature soil microplastics removal or separation technology that can be applied to practice [105, 106]. A problem that needs to be overcome urgently.

(3) Establishment of microplastic pollution evaluation system and risk assessment model

The pollution risk assessment of soil heavy metal pollution [107, 108]in past research work is relatively mature, but microplastic pollution, which can also cause harm to soil, lacks a series of ecological risk assessment models [109] and quality assessment standards. The establishment of an evaluation system for plastic abundance and the rapid unification of international standards for soil microplastic content requires further consideration.

(4) Provide constructive suggestions for the control of soil microplastic pollution

Based on the above three aspects of data support, the implementation of soil microplastic pollution control measures, in conjunction with the local government from both the source and end units, need to propose a scientific and feasible control plan. First of all, while advocating citizens to reduce the use of unnecessary plastic products, they should also manufacture easily degradable plastic mulch, films, bags and other products through clean production processes [110, 111]. Second, plastic products that are already present in our daily lives should be recycled in a timely manner to achieve the purpose of recycling. Finally, national education and prevention and control campaigns are essential.

It is worth mentioning that the focus of research in the field of microplastics has gradually shifted to the terrestrial system. At the same time, the desert, a distinctive region with a vast, untouched interior; is the best area to investigate the sources of soil microplastics outside of human activities, yet few articles and studies have been published. Scholars have tried to carry out research in the Lut and Kavir deserts of Iran [112], the Badain Jaran Desert [113] and the Mu Us Desert in Inner Mongolia [12]: microplastics in deserts are mostly from wind and sand deposition with long distance atmospheric transport. However, not nearly enough to link desert microplastics across the globe. microplastics. Similar to deserts, the polar regions, Qinghai–Tibet Plateau and other regions have paid attention to microplastics and their composite pollution in past research work, which does not match their important ecological and environmental status. Therefore, strengthening the research on soil microplastics in ecologically sensitive areas such as deserts, polar regions, and the Qinghai–Tibet Plateau, and avoiding the Polygono effect caused by microplastic pollution to the environment should also be one of the factors for future scholars to consider.

Conclusion and deficiency

Conclusions

Based on 159 English literatures retrieved from WOS databases, this paper conducts a visual analysis of the development trend of soil microplastics, and initially draws the following conclusions:

(1) The number of research results published in the field of soil microplastics published on WOS and CNKI has experienced a slow-growing stage. The country with the highest number of publications in this field is China, with 55 publications and a strong focus on international exchange, with close cooperation with Canada, New Zealand and Turkey. And the most published institution is Free Univ Berlin, followed by Chinese Academy of Sciences, Berlin Brandenburg Inst Adv Biodivers Res, Wageningen Univ&Res.

(2) Starting from key words, the current research in the field of soil microplastics contains four major components: environmental pollution and exposure, the function and health of the soil-associated medium itself, the common shape characteristics of microplastics and their influencing factors, and the combined pollution caused by microplastics, related to the eight types of soil, ingestion, heavy meals, fibres, marine environment, microplastic, metals and plants. Based on the above, it is found that the current international research in the field of soil microplastics focuses on the migration behaviour in the soil medium and the ecotoxicological effects it brings.

(3) The migration behaviour of microplastics in soil has not yet been studied in depth and further research

is needed in the future. In addition, research on soil microplastic removal or separation technologies should be promoted as soon as possible, so that a standardised microplastic pollution evaluation system and risk assessment models can be better established. At the same time, we should pay more attention to the ecologically fragile and sensitive areas, such as deserts, polar regions and the Qinghai–Tibet Plateau, and build a complete "microplastic map of the Earth".

Deficiency

It is well-known that bibliometric methods can clarify the historical context of a field and are a quick way for novices to enter the field. However, because it is presented in a statistical manner, it may obscure information about the study itself and does not have the mechanistic support of an experimental study, for example. Therefore, subsequent studies could combine a single bibliometric analysis with a model, and the results of the combined analysis may be more realistic.

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Author contributions
Z is the author of this article, and she did all the data and article Writing; S and W provided revision suggestions and financial support, among which S gave the initial conception of this paper. And the other W gives help in using the software. All authors read and approved the final manuscript On examination.

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Availability of data and materials
The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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