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Tracing research progression from comprehensive analysis to ecotoxicological effects

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Review

Micro- and nanoplastics in soils: Tracing research progression from comprehensive analysis to ecotoxicological effects

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ABSTRACT

Micro- and nanoplastics (MNPs) emissions and pollution are a growing concern due to their potential impact on ecosystems and human health, particularly in soil. This study conducts a comprehensive bibliometric analysis of 2,451 publications spanning from 2006 to 2023. The aim is to assess the research landscape, trends, contributors, and collaborative efforts related to MNPs in soil. Moreover, it examines the extensive research on the effects of MNPs on soil organisms, including earthworms, nematodes, and other fauna as well as the physical–chemical impacts, nanoscale interactions, and ecotoxicological effects on soil microorganisms. Utilizing network analysis, this study explores the global distribution of research across countries, institutions, authors, and keywords, shedding light on the interconnected scientific exploration. The findings reveal a consistent rise in research output over the past decade, reflecting worldwide interest in soil MNPs pollution. It also identifies influential authors and interdisciplinary clusters, highlighting their significant collaborations. Moreover, it pinpoints key institutions and leading journals in this area. Keyword co-occurrence and time-series analysis uncover seven significant research clusters. All provide insights into crucial MNPs aspects and their environmental and health implications. Our findings guide future research and inform strategies to combat MNPs pollution in soils, underscore the need for interdisciplinary approaches to address this complex challenge. In essence, our comprehensive bibliometric analysis serves as a valuable resource, it benefits researchers, policy stakeholders by promoting further research and guiding strategies to mitigate MNPs pollution in soils, in support of ecosystem preservation and human health protection.

1. Introduction

Plastic pollution has emerged as a global environmental problem (Andrady, 2011; Lwanga et al., 2017; Ng et al., 2018; Aurisano et al., 2021), attracting significant attention to its impact on marine ecosystems. However, recent studies have revealed another concerning aspect of plastic pollution - its presence in terrestrial ecosystems (Rillig, 2012; Rillig et al., 2017; Ya-di et al., 2022), particularly in soil (Rillig et al., 2017). Microplastics (MPs) are plastic particles measuring less than 5 mm, while nanoplastics (NPs) are even smaller, typically less than 1 μm (Kwak and An, 2021; Yu et al., 2023). Their small size makes them easily accessible to soil organisms, ranging from microorganisms to soil-

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dwelling invertebrates, which can inadvertently consume or encounter these particles. Soil micro- and nanoplastics (MNPs) pollution has emerged as a critical issue with potential far-reaching implications for soil health, biodiversity, and ecosystem functioning (Askham et al., 2023; Horton et al., 2017; Kwak and An, 2021; Vaccari et al., 2022). The widespread presence of plastic debris in terrestrial ecosystems highlights soil MNPs pollution as an urgent environmental concern. These plastic particles can originate from various sources, including fragmentation of larger plastics, industrial processes, and agricultural activities (de Souza Machado et al., 2019; Guo et al., 2020). Introduction of plastic particles into soil can occur through multiple pathways, such as the application of plastic-based mulches in agriculture, the deposition of airborne MNPs, and the disposal of plastic waste in landfills (Guo et al., 2020; Tian et al., 2022). Once in the soil, these MNPs can persist and accumulate, posing risks to soil organisms and potentially entering the food chain (Horton et al., 2017).

Soil plays a crucial role in ecosystems, serving as a vital component that supports plant growth, water cycling, and nutrient cycling, among other critical functions (Brussaard, 1997). However, MNPs contamination in soil has the potential to severely impact these functions. Understanding the toxicological implications of MNPs on soil biota is crucial for several reasons. First, the soil ecosystem plays a fundamental role in nutrient cycling, plant growth, and carbon sequestration. Any disruptions in this delicate balance can have cascading effects on terrestrial ecosystems. Second, MNPs can enter the food chain through soil-dwelling organisms, potentially posing risks to higher trophic levels, including humans who consume crops grown in MNPs-contaminated soil (Allen et al., 2023; Li et al., 2023a). From a toxicological perspective, the presence of MNPs in the soil may introduce or magnify toxic effects on soil organisms. These plastic particles can act as vectors, absorbing and releasing various environmental pollutants, including persistent organic pollutants and heavy metals, thus exacerbating their toxic effects on soil biota. The interaction between these contaminants and MNPs can lead to complex, compound-specific toxicity dynamics, posing significant challenges for soil health assessments. Specifically, (i) MNPs pollution in soil can have detrimental effects on soil microorganisms, soil fauna, and overall biodiversity, disrupting the balance and stability of soil ecosystems (Lin et al., 2020; Wang et al., 2022c); (ii) Accumulation of MNPs lead to a decline in soil quality, affecting soil structure, water-holding capacity, and nutrient cycling, thereby impacting crop yields and the sustainable utilization of soil (Wang et al., 2019a; Wang et al., 2019b; Yu et al., 2021). (iii) Soil MNPs be absorbed by plants and enter the food chain, posing potential risks to human health and animal well-being, particularly for consumers of crops and carnivorous animals (Huerta Lwanga et al., 2017). Furthermore, the impacts of soil MNPs pollution extend beyond the soil ecosystem. These particles can enter water bodies through transport and runoff, potentially contaminating freshwater and marine environments (Gouin, 2021; Horton and Dixon, 2018; Horton et al., 2017). Additionally, soil MNPs act as carriers for other pollutants, such as heavy metals and organic contaminants, exacerbating the ecological risks associated with their presence (Fu et al., 2021; Yang et al., 2022).

Understanding the current state of research on soil MNPs pollution is essential for guiding future studies and informing effective mitigation strategies. In this regard, bibliometric analysis, a quantitative method for analyzing scientific publications, proves to be valuable. Bibliometric analysis serves as a powerful tool for systematically evaluating and quantifying scientific literature in a specific field (Li et al., 2022a; Li et al., 2022b). By analyzing publication trends, research themes, author collaborations, and the geographical distribution of studies, bibliometric analysis can offer valuable insights into the global research landscape of soil MNPs pollution. Through bibliometric analysis, we can identify trends in research output, such as the growth in the number of publications over time and the geographic distribution of research efforts (Chen, 2017; Chen et al., 2010; Li et al., 2021). Furthermore, the analysis of keywords and subject categories reveals the evolving focus areas within the field, highlighting key research directions and emerging topics (Decouttere et al., 2021; Liu et al., 2021). Author collaborations and co-citation networks offer insights into the collaborative nature of research and the influential authors and institutions driving the field forward (Li et al., 2022a). The application of bibliometric analysis to the study of soil MNPs pollution offers several advantages. It allows researchers to gain a comprehensive overview of the research landscape, identify knowledge gaps, and prioritize future research areas (Li et al., 2022b). Moreover, it can assist policy stakeholders in making informed decisions by providing a scientific basis for developing regulations and management strategies to mitigate soil MNPs pollution (Fig. 1**A**).

This study presents a comprehensive bibliometric analysis of peer-reviewed research articles focused on soil MNPs pollution. The analysis aims to explore the evolving research trends, identify key research directions, and highlight knowledge gaps. Our specific research questions include but are not limited to: (i) Global research trends: Through bibliometric analysis, we investigate recent trends in soil MNPs contamination research worldwide. This includes examining the growth in research publications, the geographical distribution of studies, and collaborative networks. (ii) Major research directions: Analyze keywords and topics in research papers to identify the primary research directions and emerging focus areas within soil MNPs contamination research. These areas may include detection methods, ecological risk assessment, pollution source tracking, mitigation strategies, and the toxicological implications of MNPs on soil biota. Addressing these research questions will provide in-depth insights into the global status and research hotspots regarding soil MNPs contamination. Furthermore, understanding the toxicological consequences of MNPs on soil organisms can offer valuable context for comprehending the broader ecological implications. In summary, the findings of this study will not only contribute to advancing knowledge on soil MNPs pollution and its toxicological ramifications but also provide a foundation for future research and policy development aimed at mitigating the environmental impacts of plastic pollution in soil ecosystems.

2. Material and methods

In order to perform a bibliometric analysis of soil MNPs pollution, we utilized data extracted from the Web of Science database. We conducted a search in the database using the retrieval formula "soil and micro- and nanoplastics" to identify relevant publications. A total of 2,451 documents were obtained, which formed the basis for our analysis. We utilized various tools and software programs to analyze the bibliometric data, including VOSviewer, CiteSpace, and R. Each of these tools provides unique functionalities and insights into various aspects of the data.

VOSviewer is a widely employed tool for visualizing and exploring bibliometric networks. It facilitates the identification of research clusters, the visualization of co-authorship networks, and the mapping of keyword co-occurrence networks (Van Eck and Waltman, 2010; Van Eck and Waltman, 2017). By utilizing VOSviewer, we can generate visual representations of the research landscape, highlighting key research areas, influential authors, and collaborative networks in the field of soil MNPs pollution. Within VOSviewer, the density map reveals that areas with higher density indicate a greater number of connections between institutes, suggesting a more cohesive network in those regions. Conversely, areas with lower density represent fewer connections, indicating potential gaps or less active collaborations. The weights of links indicate the strength of connections between institutes, while the total link strength represents the cumulative strength of all connections. CiteSpace is another powerful tool for bibliometric analysis that focuses on detecting emerging trends and identifying critical publications. It allows us to conduct co-citation analysis to uncover influential articles and authors, visualize citation networks, and identify research fronts and knowledge bases (Chen et al., 2012). By employing CiteSpace, we can gain insights into the intellectual structure of the field, identify pivotal papers, and track the evolution of research themes over time.

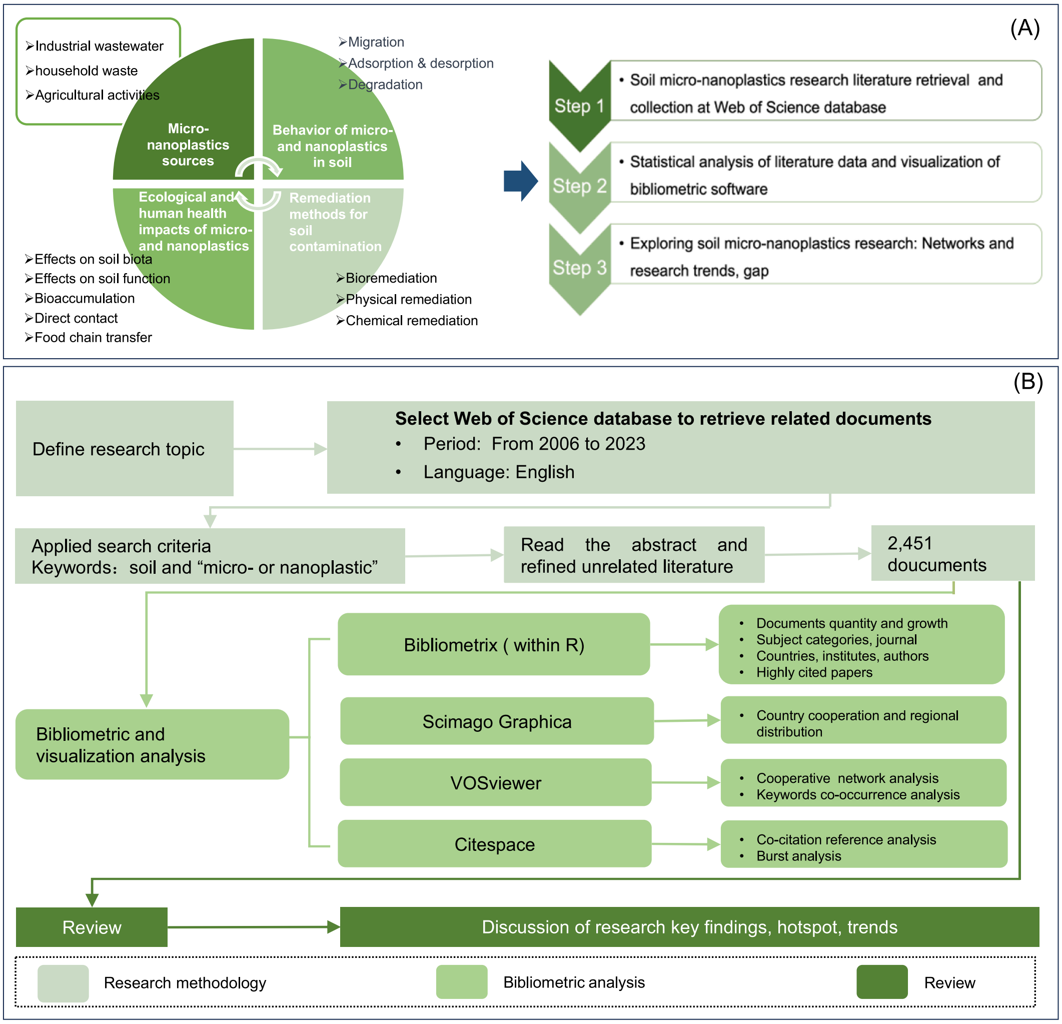

Fig. 1. The applied framework of the bibliometric analysis of research focusing on micro- and nanoplastics (MNPs) soil pollution (A); Flow chart of literature data retrieval and processing analysis (B).

Additionally, we utilized the R language for statistical analysis and data visualization. R provides a flexible and comprehensive environment for processing bibliometric data, conducting statistical tests, and creating interactive visualizations (Viana-Lora and Nel-lo-Andreu, 2022; Vieira et al., 2021; Xi et al., 2022). With R, we can perform various analyses, including publications trend analysis, author collaboration analysis, and keyword analysis, to gain a comprehensive understanding of the research landscape in the field of soil MNPs pollution.

The combination of VOSviewer, CiteSpace, and R language analysis allows us to explore the bibliometric data from multiple perspectives, providing a robust and comprehensive analysis of the research trends and knowledge domains within the field of soil MNPs pollution. By employing these methods and tools, our aim is to uncover the patterns, trends, and emerging research directions in soil MNPs pollution. The analysis will provide valuable insights into the current state of research, identify knowledge gaps, and guide future studies in this critical area of environmental research (Fig. 1**B**).

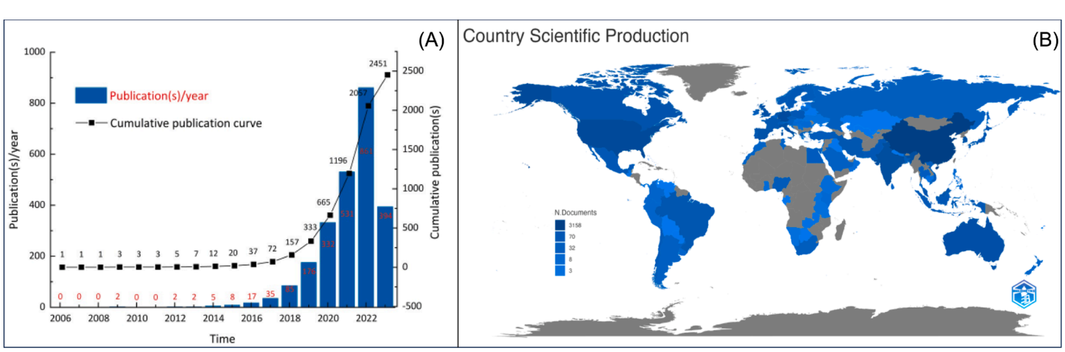

Fig. 2. Annual number and accumulated number of scientific published documents in 2006–2023 about soil MNPs studies (A), and country scientific production distribution (B).

3. Results

3.1. Publications output overview and geographical distribution characteristics

The data presents in Fig. 2**A** illustrates the publications trends in the field of soil MNPs pollution from 2006 to 2023. In this analysis, we examine the trends and emphasize important observations: (i) Initial years with limited research: From 2006 to 2009, there were no or very few publications focused on soil MNPs pollution. This indicates a limited initial awareness and research interest in this specific area during those years. The absence of publications suggests that the potential impacts of MNPs on soil ecosystems were not yet a prominent research focus; (ii) Gradual growth and early stages: The data shows a gradual increase in the number of publications from 2009 to 2015. During this period, the field of soil MNPs pollution began to gain attention, with a small but growing number of researchers exploring this topic. The steady but modest growth suggests that the research community was beginning to recognize the importance of studying MNPs in soil environments; (iii) Accelerated growth: From 2016 onwards, there was a significant acceleration in the number of publications. The data demonstrates a remarkable increase in publications each year, indicating a surge in research activity and heightened interest in the field of soil MNPs pollution. This rapid growth reflects the growing recognition of the potential ecological impacts and the need for scientific investigation in this area; (iv) Exponential growth: Notably, from 2018 to 2023, the publication numbers show an exponential growth pattern. This exponential trend suggests a growing urgency to comprehend and tackle the issue of soil MNPs pollution. The substantial increase in publications during this period highlights the growing global concern and the need for comprehensive research to assess the sources, fate, and impacts of MNPs on soil ecosystems. The exponential growth observed in recent years suggests that the research community's interest and engagement in this field will persist, leading to further advancements in understanding the effects of MNPs on soil health and ecosystem functioning. Overall, the publication trends reveal a significant growth in research efforts focused on soil MNPs pollution. The gradual growth in the early years, followed by accelerated and exponential growth in recent years, reflects the increasing recognition of the importance of studying MNPs in soil environments. The upward trend of publications reflects an increasing commitment to addressing the ecological implications of soil MNPs pollution and developing strategies to mitigate plastic contamination in soils. Ongoing research and collaboration are crucial in furthering our understanding of this issue and implementing effective solutions to preserve soil health and ecosystem sustainability.

The examination of scientific production concerning soil MNPs pollution revealed substantial research activity in multiple countries. China emerged as the leading contributor, having the highest frequency of publications, which reflects its dedication to studying the environmental impact of plastic pollution on soil ecosystems. The United States ranked second, displaying significant research output in this field, followed by Germany, indicating notable contributions driven by thi emphasis on environmental research. India exhibited a notable research output, reflecting the country's growing concern for environmental issues. Italy and the United Kingdom additionally made substantial contributions, emphasizing their commitment to comprehending the consequences of plastic waste. Moreover, countries including Australia, South Korea, Spain, the Netherlands, and Canada actively participated, demonstrating a global endeavor address soil MNPs pollution. This diverse international representation highlights the collective concern and approach adopted by researchers worldwide in investigate the impacts of MNPs on soil ecosystems.

3.2. Major journals and scientific publications in soil MNPs research

3.2.1. Leading journals

Table 1 presents a compilation of primary source journals that have published research on soil MNPs. The analysis comprises essential metrics, including the number of publications (NP), total citations (TC), h-index, and g-index. Science of the Total Environment distinguishes itself with 431 publications and a notable h-index of 73, signifying significant influence in the field. Similarly, Environmental Pollution boasts 217 publications and a robust h-index of 65. These two journals have made active contributions to the knowledge base on soil MNPs since 2016. Other noteworthy journals encompass Journal of Hazardous Materials, Chemosphere, and Environmental Science & Technology, which have published substantial research on the topic. It is worth noting that the Water Research journal shows a relatively lower number of publications (45), yet possesses a commendable h-index of 28, indicating its influential in this field. Overall, these primary source journals play a vital role in advancing our comprehension of the environmental implications associated with soil MNPs.

3.2.2. Key publications in soil MNPs research

Table 2 presents the most cited documents globally in bibliometric analysis. These documents have made significant contributions to their respective research fields and have garnered considerable attention and recognition within the scientific community. Among the highly cited papers, "Barnes dka, 2009″ has the highest TC count of 3,012, accompanied by a TCPY of 200.80 and an NTC value of 1.31. This indicates that the paper has been cited multiple times and continues to receive citations over the years. Similarly, "Teuten el, 2009″ follows with a TC of 1,592, a TCPY of 106.13, and NTC of 0.69, highlighting its influence and impact in the field. Other notable contributions include "Horton aa,

Table 1
Primary source journal more concerns with soil MNPs.

Element	NP	TC	h_index	g_index	PY_start	IF (2022)
Science of the Total Environment	431	20,269	73	131	2016	10.754
Environmental Pollution	217	12,543	65	108	2016	9.988
Journal of Hazardous Materials	203	6,187	44	72	2018	14.224
Chemosphere	133	3,844	33	60	2017	8.943
Environmental Science & Technology	80	10,928	36	80	2014	11.357
Marine Pollution Bulletin	74	3,785	30	61	2013	7.001
Environmental Science and Pollution Research	66	1,796	17	42	2017	5.19
Water Research	45	4,122	28	45	2015	13.4
Water	34	430	12	20	2019	3.53
Environmental Research	33	591	12	24	2017	8.431
Frontiers in Environmental Science	33	330	10	18	2020	5.411
Ecotoxicology and Environmental Safety	30	804	12	28	2019	7.129
Journal of Environmental Management	23	254	9	15	2020	8.910
Chemical Engineering Journal	22	626	12	22	2020	16.744
Sustainability	22	340	7	18	2020	3.889

NP = number of publications, PY-start = published year start, IF = impact factor.

Table 2
Most globally cited documents.

Paper	DOI	TC	TCPY	NTC
Barnes dka, 2009	https://doi.org/10.1098/rstb.2008.0205	3,012	200.80	1.31
Teuten el, 2009	https://doi.org/10.1098/rstb.2008.0284	1,592	106.13	0.69
Horton aa, 2017	https://doi.org/10.1016/j.scitotenv.2017.01.190	1,400	200.00	4.59
Eerkes-medrano d, 2015	https://doi.org/10.1016/j.watres.2015.02.012	1,308	145.33	3.17
Auta hs, 2017	https://doi.org/10.1016/j.envint.2017.02.013	1,102	157.43	3.61
Reid aj, 2019	https://doi.org/10.1111/brv.12480	1,066	213.20	10.47
Alimi os, 2018	https://doi.org/10.1021/acs.est.7b05559	1,043	173.83	5.99
Machado aad, 2018	https://doi.org/10.1111/gcb.14020	832	138.67	4.78
Li wc, 2016	https://doi.org/10.1016/j.scitotenv.2016.05.084	758	94.75	2.07
Duis k, 2016	https://doi.org/10.1186/s12302-015–0069-y	752	94.00	2.06
Rillig mc, 2012	https://doi.org/10.1021/es302011r	724	60.33	2.00
Steinmetz z, 2016	https://doi.org/10.1016/j.scitotenv.2016.01.153	703	87.88	1.92
Nizzetto l, 2016	https://doi.org/10.1021/acs.est.6b04140	691	86.38	1.89
Vianello a, 2013	https://doi.org/10.1016/j.ecss.2013.03.022	613	55.73	1.58

TC = Total Citation, TCPY = Total Citation per Year, NTC = Normalized Total Citation.

2017″ with a TC of 1,400, ″Eerkes-medrano d, 2015″ with a TC of 1,308, and "Auta hs, 2017″ with a TC of 1102. These papers have garnered significant attention in their respective areas of study, as evident from their high TC values and relatively high TCPY and NTC scores. ″Reid aj, 2019″ stands out with a high TCPY of 213.20 and an NTC value of 10.47, indicating a significant impact and influence within a relatively short timeframe. Similarly, "Alimi os, 2018″ and ″Machado aad, 2018″ have noteworthy TCPY and NTC values, suggesting their recognition and relevance in their respective research domains. Overall, the presented data underscores the significance and impact of these globally cited documents in the field of bibliometrics analysis. These papers have received substantial citations, indicating their influence on subsequent research and the scientific community. Their high TCPY and NTC scores further validate their continuous relevance and contribution to their respective research fields.

3.3. *Global network relationships*

3.3.1. *Institutional collaboration network*

The density figure in VOSviewer (Fig. 3**A**) provides a visual representation of the density of connections between institutes in the network. It helps to understand the concentration and distribution of collaborative relationships within the research landscape. Notably, the Chinese Academy of Sciences and the University of Chinese Academy of Sciences stand out with high link weights (82) and a significant total link strength (758,059), indicating a strong and extensive collaboration network associated with these institutions. Other notable institutes demonstrating substantial link weights (82) and considerable total link strength values (ranging from 210,878 to 334,568) include Northwest A&F University, East China Normal University, and Nankai University. These institutes actively engage in collaborative efforts within the network. When considering the number of documents, Wageningen University & Research takes leads with a weight of 82, indicating a substantial publications output associated with this institute. This is further supported by their significant citation count (4,187), suggesting the impact and visibility of their research. It's important to note that some institutes may have lower link weights or total link strength but still contribute significantly to the research landscape. For example, Free University Berlin, despite having a relatively lower link weight (82), has a high citation count (5,415), indicating the quality and impact of their research output.

3.3.2. *Author collaboration network*

The analysis of author collaborations offers valuable insights into the collaborative nature of research on soil MNPs pollution. A network visualization of co-authorship patterns revealed clusters of researchers collaborating on various topics within the field. Fig. 3**B** showcases the co-authorship network, highlighting prominent research clusters and

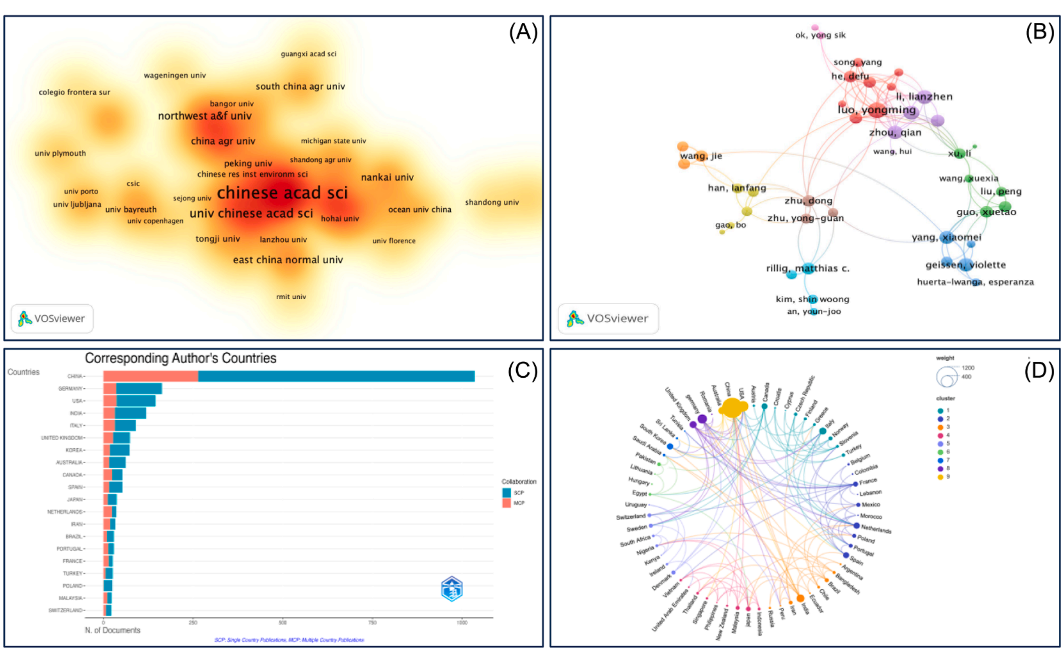

Fig. 3. Collaboration density map of co-author relationships among key research institutions (A); Key author network based on co-authorship analysis of soil MNPs studies (B); Analysis of single country publications (SCP) and multiple country publications (MCP) (C); Collaboration network of countries (D).

their interconnections. Fig. 3**C** provides information on the distribution of corresponding authors' countries in bibliometric analysis. China leads the list with 1,035 articles, out of which 771 are single-country publications and 264 are multiple-country publications. The MCP frequency for China is 0.41, indicating significant collaboration with researchers from other countries. Germany follows with 163 articles, of which 127 are single-country publications (SCP) and 36 are multiple-country publications (MCP). Although Germany has a lower number of articles compared to China, its MCP ratio is higher at 0.221, suggesting substantial international collaboration in research. The United States (USA) ranks third with 145 articles, of which 108 are SCP and 37 are MCP. With a lower MCP frequency of 0.057, the USA exhibits a comparatively lower level of international collaboration. India and Italy also feature prominently in the analysis, with 119 and 90 articles respectively. Both countries have notable MCP ratios, indicating active involvement in international research collaborations. Among other countries, the United Kingdom, Korea, Australia, Canada, and Spain demonstrate varying levels of MCP occurrence and ratios. It is worth mentioning that the Netherlands, Iran, Portugal, France, and Turkey also contribute significantly to research in this field. Overall, the data provides insights into the distribution and collaboration patterns among corresponding authors' countries in the study of soil MNPs. The results highlight the global nature of research on this topic, with several countries actively participating in international collaborations to advance our understanding of the subject matter.

3.3.3. International collaboration trends

The analysis of scientific collaboration in the field of soil MNPs pollution revealed interesting patterns of international cooperation (Fig. 3**D**). Collaborations between countries like France and Algeria, Brazil and Argentina, Spain and Argentina, and the USA and Argentina highlight the global effort to understand the impact of plastic waste on soil ecosystems across different regions. Partnerships between China and Australia, Germany and Australia, and the USA and Australia demonstrate a shared interest in investigating the presence and effects of soil MNPs. Additionally, collaborations between China and the Netherlands, Canada and France, and Germany and the United Kingdom indicate a collaborative approach to addressing the challenges of soil pollution caused by plastic particles. These findings emphasize the importance of cross-border collaborations and the global nature of research on soil MNPs pollution, fostering knowledge exchange and advancing scientific understanding worldwide.

3.4. Keyword co-occurrence, dynamics trends and emerging fronts analysis

3.4.1. Keyword network structure and research hotspots clusters analysis

The keyword co-occurrence analysis yielded seven clusters, each represented by a dominant keyword. As shown in Fig. 4**A**, Cluster 1 (red) focuses on "microplastics" and includes keywords such as heavy metals, earthworms, microbial community, and phytotoxicity, emphasizing their impact on soil health and agriculture. Cluster 2 (green) revolves around "soil" and encompasses pollution, sediment, plastic, freshwater, and land use, emphasizing the relationship between soil and environmental contamination. Cluster 3 (blue) centers on "plastic pollution" and covers issues such as marine litter, waste management, ecological risk, and circular economy. Cluster 4 (yellow) emphasizes "microplastic pollution" and its association with transport, distribution, environment, COVID-19, and human health. Cluster 5 (purple) focuses on "nanoplastics" and their effects on toxicity, adsorption, oxidative stress, and risk assessment. Cluster 6 (light blue) revolves around "sewage sludge" and includes keywords such as FTIR, wastewater, fibers, and microfibers, highlighting the role of wastewater treatment plants and their impact on the environment. Finally, Cluster 7 (orange) centers on specific types of plastic such as "polyethylene" and "polystyrene" and explores their biodegradation, degradation, and interactions with microorganisms and biofilms. These clusters collectively contribute to our understanding of soil MNPs, encompassing their ecological, environmental, and health implications.

Through the keyword co-occurrence analysis of seven clusters and the construction of a time-series keyword co-occurrence network Fig. 4**B**, we have obtained significant research findings in the field of soil MNPs. In the keyword co-occurrence network, the emergence of new keywords such as bioavailability, biochar, COVID-19, enzyme activity, and leachate represent emerging research topics, highlighting the forefront progress and new areas of interest in the current research domain. Moreover, the presence of the COVID-19 keyword indicates researchers' growing interest in exploring the relationship between MNPs and infectious diseases, which holds significant implications for public health and environmental protection. The time-series keyword co-occurrence network presents a comprehensive overview of the research landscape in the field of soil MNPs and aids in identifying current research trends.

3.4.2. Evolution of specific soil MNPs research themes

The thematic map of soil MNPs research, depicted in Fig. 5**A**, illustrates a keyword mapping of the title, revealing seven distinct clusters. These clusters are as follows (i) soil effects and polystyrene; (ii) review, pollution, and environment; (iii) microplastics, soils, and nanoplastics; (iv) microplastic and plastic distribution; (v) eisenia, earthworm, and fetida; (vi) media, porous, saturated; and (vii) antibiotics resistance genes. Each cluster represents a specific area of research and demonstrates the interconnectedness of keywords within that cluster. By visually depicting the relationships between keywords and their corresponding clusters, the thematic map provides a comprehensive overview of the research landscape in the field of soil MNPs studies.

The analysis of the thematic evolution in soil MNPs research reveals

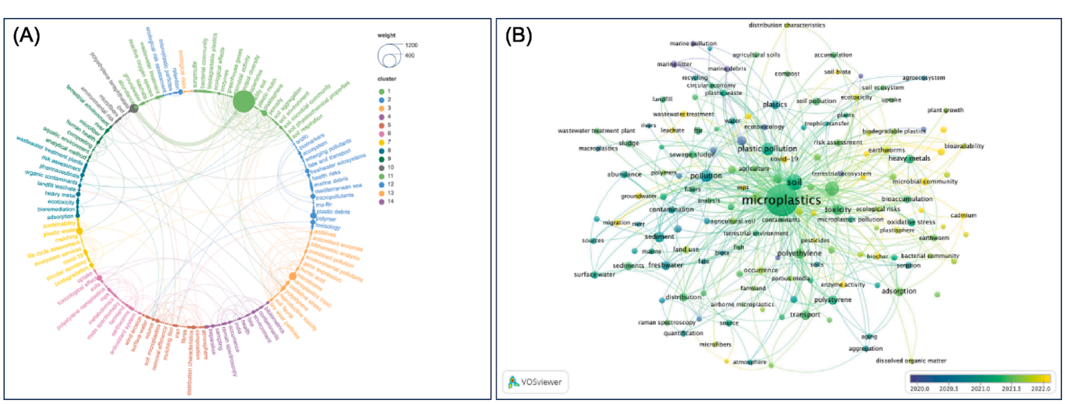

Fig. 4. Keyword co-occurrence network on MNPs and soil with other related keywords independently (A); Time series display of keyword co-occurrence of soil MNPs studies (B).

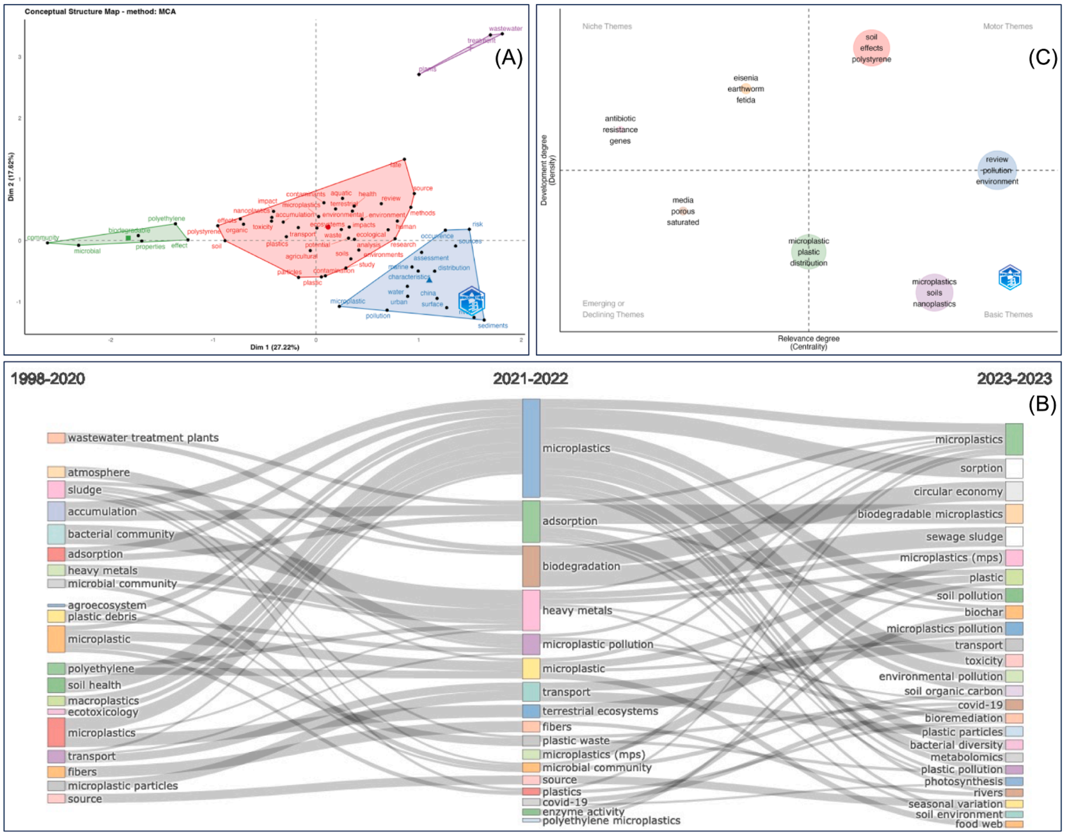

Fig. 5. Thematic map of soil MNPs studies focus (A); Thematic evaluation of soil MNPs studies the keywords from abstract (B); Conceptual structure map soil MNPs studies (C).

a gradual shift towards a more comprehensive understanding of the topic (Fig. 5**B**). Specifically, there has been a noticeable transition from focus on "accumulation" during the years 1998–2020 to "adsorption" and "uptake" in the years 2021–2022. This evolution signifies a growing interest in comprehending the mechanisms of soil contamination and aging related to MNPs, as indicated by the continuous prominence of the keyword "adsorption". Furthermore, the emergence of keywords like "microplastic pollution", "microplastics", and "plastic pollution" in recent years signifies a heightened concern for the environmental pollution caused by MNPs across various ecosystems, including freshwater, marine, and terrestrial habitats. This aligns with the global recognition of MNPs as a pervasive environmental issue. Additionally, research on the interactions between MNPs and other environmental factors has expanded, as evidenced by the introduction of keywords such as "microbial community", "heavy metals", and "bacterial community". This shift indicates a focus on exploring the complex relationships between MNPs and ecological constituents, with an emphasis on their potential impacts on microbial communities and the bioaccumulation of heavy metals. Moreover, the interdisciplinary nature of this field is reflected in the emergence of keywords like "biodegradation", "wastewater treatment plants", and "polyethylene". These keywords highlight the involvement of a variety of disciplines, ranging from environmental science to engineering and chemistry, which is crucial for developing effective strategies to mitigate the impact of MNPs pollution.

Significantly, the term "COVID-19″ has garnered attention in soil MNPs research. This reflects the influence of the global pandemics on research priorities and the increased scrutiny of the potential implications of MNPs in relation to the crisis. The emphasis on COVID-19 highlights the urgency to investigate the possible links and impacts between MNPs and the pandemic, contributing to the development of strategies for mitigating their combined effects on soil ecosystems and human well-being.

In summary, the thematic evolution in soil MNPs research signifies a shift towards a more comprehensive understanding of the sources, distribution, fate, and environmental impacts of MNPs. The identification of key clusters and their associated keywords provides a roadmap for future research, facilitating the addressing of knowledge gaps and the development of targeted solutions for mitigating MNPs pollution.

The results of the multiple correspondence analysis unveil four distinct clusters, each providing insights into different aspects of MNPs research, as depicted in Fig. 5**C**. Cluster 1 incorporates terms that primarily related to the investigation of MNPs and their environmental impacts. These terms, such as "soil", "effects", "review", "plastic", "distribution", "environment", "nanoplastics", and "contamination", collectively represent the study of how MNPs affect the environment and the associated risks. Cluster 2 emphasizes the association between MNPs pollution and its distribution in specific contexts, featuring terms such as "China", "water bodies", "rivers", and "urban areas". This cluster provides insights into the spatial distribution of MNPs pollution and its potential risks in various ecosystems, including marine environments. Focusing on the properties and impacts of polyethylene and polystyrene. This Cluster 3 delves into the microbial interactions of polyethylene and polystyrene. This cluster involves terms like "polyethylene", "microbial", "polystyrene", and "properties", which explore the specific characteristics of these plastics and their ecological implications. Lastly, Cluster 4 revolves around the treatment and management of plastic waste. It encompasses terms such as "plants", "treatment", "wastewater", and "biodegradable", highlighting the significance of strategies for managing plastic waste, especially in the context of wastewater treatment and the use of biodegradable materials.

3.4.3. *Emerging research fronts in soil MNPs research*

The keyword burst analysis conducted using CiteSpace elucidates significant trends and shifts in research focus within the field. It helps identify emerging research fronts and knowledge bases. These research fronts represent evolving research areas that have gained substantial attention in recent years. As illustrated in Fig. 6, key areas of investigation from 2009 to 2020 included litter and persistent organic pollutants, with a strong emphasis on the marine environment and the accumulation of debris. Notably, research attention expanded to encompass the presence and impact of plastic debris, ingestion by organisms such as Mytilus edulis l and zooplankton, and the occurrence of synthetic fibers in aquatic environments. In recent years, there has been a growing interest in the effects of MNPs in terrestrial ecosystems, including soils. Notable research fronts within soil MNPs pollution included “ecotoxicology of microplastics”, “plastic degradation in soil”, and “microplastics in agricultural systems”. These emerging research fronts indicate the dynamic nature of the field and highlight the need for further exploration of the fate, distribution, and potential ecological impacts of MNPs in soil environments. The analysis underscores the importance of understanding the extent of contamination and the associated risks to develop effective mitigation strategies and safeguard ecosystem health.

4. Discussion

4.1. Discussion on overall characteristics

The bibliometric analysis offers a comprehensive perspective on research related to soil MNPs pollution. This discussion presents key findings and implications across various dimensions, including research interest, geographical distribution, collaborative networks, research themes, emerging fronts, knowledge gaps, and policy implications. The results of the bibliometric analysis provide a thorough overview of the research landscape surrounding soil MNPs pollution. In this section, we discuss the implications of the findings and highlight important aspects that require further consideration. Overall, the bibliometric analysis provided valuable insights into the research landscape of MNPs pollution. The results demonstrated the increasing research interest, the global distribution of research efforts, collaborative networks, and emerging research fronts within the field. These findings will inform future research directions, facilitate knowledge exchange, and support evidence-based decision-making in the development of effective strategies for mitigating soil MNPs pollution.

4.1.1. Increasing research interest

The steady growth in the number of publications on soil MNPs pollution reflects the increasing recognition of this issue as a global environmental concern (Aihong et al., 2021; Horton et al., 2017; Wang et al., 2022a). The rising research interest indicates the urgency to understand the potential impacts of plastic pollution on soil ecosystems and underscores the need for effective mitigation strategies. The growing awareness of the impacts of MNPs in the soil environment has fostered interdisciplinary studies and international collaborations.

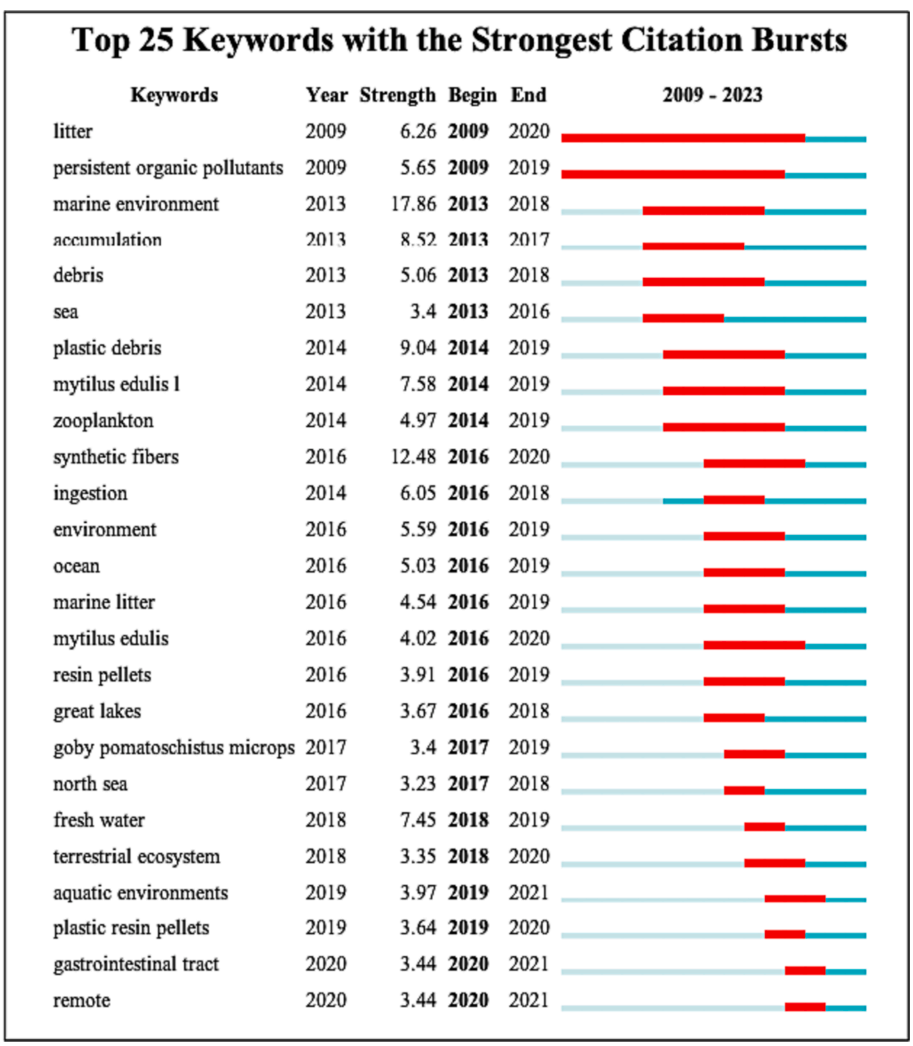

Fig. 6. Top 25 Keywords with the Strongest Citation Bursts. Note: Each grid represents a year. Red grids indicate the year when a particular term started to be frequently used. The intensity represents the strength of a term’s occurrence in research.

These initiatives aim to unravel the complex dynamics of MNPs, exploring not only their physical, chemical, and biological interactions with soil constituents but also their potential detrimental effects on soil health and productivity (Tian et al., 2022; Vaccari et al., 2022). To address this environmental challenge, the academic community has organized various conferences, symposiums, and workshops worldwide, focusing on soil MNPs pollution (Cao et al., 2017). Furthermore, an increase in research publications has expanded the scope of exploration, shifting focus towards understanding not only the sources, fate, and transport of MNPs in soil, but also the efficacy of diverse remediation strategies (Patil et al., 2022).

4.1.2. Geographical distribution

The concentration of research efforts in regions characterized by high plastic consumption and production, such as Europe, North America, and East Asia (Auta et al., 2017), suggests that these regions are at the forefront of addressing soil MNPs pollution. With advanced research infrastructure and capabilities, these areas have successfully pioneered novel investigative approaches to understand and mitigate the issue. However, the emergence of research hubs in other regions, including South America and Southeast Asia, signifies the global spread of research interest and highlights the importance of addressing this issue on a broader scale (Torres-Agullo et al., 2021; Wang et al., 2022a). Encouragingly, this expansion allows for studying the impacts of MNPs under diverse environmental conditions, given the regions' varying climates and soil types. Nevertheless, the current research landscape also reveals potential disparities. Regions such as Africa and Central Asia are underrepresented in the body of research, despite the high probability of plastic pollution due to inadequate waste management practices (Deme et al., 2022; Mihai et al., 2021). This research gap emphasizes the necessity for increased international collaboration and resource allocation to support studies in these regions.

4.1.3. Collaborative networks

Research clusters and collaborations drive knowledge exchange (Lusher et al. 2021). By promoting cross-disciplinary dialogue, these collaborations generate holistic solutions to the problem of soil MNPs pollution. Inclusivity enhances diversity of thought and reflects global magnitude (Africa, Central Asia). Strengthening these networks not only deepens our understanding but also enables the development of effective solutions. Identifying research clusters and collaborative networks underscores the collaborative nature of soil MNPs pollution research. Encouraging collaborative among researchers, institutions, and countries is essential for sharing knowledge, expertise, and resources (Lusher et al., 2021). Such collaboration can catalyze interdisciplinary approaches and pave the way for comprehensive solutions to soil MNPs pollution. Typically, these collaborations materialize as joint publications, shared research projects, or the exchange of datasets and methodologies. Importantly, they facilitate the pooling of resources, cross-pollination of unique perspectives and insights, and contributing to a more comprehensive and robust understanding of soil MNPs pollution. Furthermore, these international collaborations underscore the global recognition of soil MNPs pollution as a shared challenge. The cooperative alignment of research efforts across national borders signifies the understanding that soil MNPs pollution transcends geographical boundaries and that proposed solutions must be considered in a global context.

Collaborative partnerships provide a platform for interdisciplinary dialogue, which is crucial due to the intricate nature of soil MNPs pollution. This issue spans multiple fields, encompassing disciplines such as chemistry, ecology, soil science, toxicology, and environmental health. By promoting cross-disciplinary dialogue, research networks can stimulate innovation and foster the development of comprehensive solutions to address soil MNPs pollution. Nonetheless, further efforts are required to extend the scope of these networks and ensure inclusivity and equity. Incorporating researchers from underrepresented regions in the literature, such as Africa and Central It is of utmost importance to include researchers from underrepresented regions such as Africa and Central Asia in these networks. This inclusivity not only promotes diversity of thought but also ensures that research efforts reflect the global magnitude of the problem. Therefore, while the existing research collaborations in the realm of soil MNPs pollution are indeed a positive development, it is imperative to continuously strengthen and diversify these networks to maximize their potential in advancing our understanding and providing solutions to the issue of soil MNPs pollution.

4.1.4. Research themes and keywords

The research themes and keywords prevalent in this field reflect the key areas of focus. The emphasis on topics such as "microplastics", "analytical methods", and "ecological impact" underscores the significance of comprehending the sources, fate, and effects of MNPs in soil ecosystems (Jin et al., 2022; Tian et al., 2022; Zhao et al., 2022). Future research should continue to explore these themes while also addressing emerging keywords and topics to broaden our understanding of the complexities surrounding this issue. The frequent mention of "microplastics" indicates the specific focus on these types of plastic pollution, likely due to their widespread presence and potential impact on soil health and productivity. The intricacies of microplastic behavior in soils, including their transport, accumulation, and degradation, remain a critical area for investigation. The prevalence of the theme "Analytical methods" suggests an ongoing need to develop reliable, sensitive, and standardized techniques for detect, quantify, and characterize MNPs in soils. This is essential as the accuracy of our findings and the effectiveness of our remediation strategies heavily depend on these methodologies. The theme of "ecological impact" reflects substantial research efforts aimed at understanding the implications of MNPs for soil biota and ecosystem services. This includes studies on the bioaccumulation of MNPs in soil organisms, their effects on biodiversity, nutrient cycling, and soil structure, among others.

However, it is equally crucial to explore emerging keywords and topics that could provide novel insights into this complex issue. For instance, themes such as the influence of climate change on the distribution and impacts of soil MNPs, the socio-economic aspects of soil plastic pollution, and the potential for bio-based plastics as a sustainable alternative are deserving of increased attention.

4.1.5. Emerging research fronts

The identification of emerging research fronts reveals areas where new knowledge is being generated and where future research efforts can be directed. These research fronts, such as "ecotoxicology of microplastics", "plastic degradation in soil", and "remote", highlight the need for comprehensive assessments of the ecological impacts of MNPs on soil organisms and ecosystems (Gudeta et al., 2023; Li et al., 2023b; Tian et al., 2022; Ya-di et al., 2022). The focus on the "ecotoxicology of microplastics" demonstrates the urgent need to understand toxic effects associated with chemicals in microplastics on soil organisms. Crucial aspects of this research area include studying the interactions between microplastics and other pollutants, elucidating the mechanisms driving their toxicity, and assessing the long-term implications for soil health and functionality.

Another active research front, "plastic degradation in soil", emphasizes the importance of investigating the fate of plastics in soil environments. This research entails unraveling the complex interplay of physical, chemical, and biological processes that govern the transformation and degradation of plastics in the soil. A comprehensive understanding of these processes could reveal potential risks of secondary pollution, such as the release of plastic additives and plastic-derived contaminants. "Remote sensing of plastic pollution" is an emerging research front that signifies advancements in pollution monitoring tools. Remote sensing offers a potentially powerful method for tracking and mapping plastic pollution on a large scale. These technologies can provide unparalleled spatial and temporal data, fostering a better comprehension of plastic pollution's distribution patterns, hotspots, and trends.

4.2. Ecotoxicological effects of MNPs in soil

The investigation of the ecological toxicity of MNPs on the soil ecosystem has become a prominent research focus, as indicated by the analysis of keywords and the identification of emerging trends. This aspect presents both a current research hotspot and a future research challenge. Based on these observations, this section offers an in-depth discussion and comprehensive overview of this issue.

4.2.1. Negative effects of micro- and nanoplastics on soil organisms

Soil organisms, including microorganisms and soil animals, play crucial roles vital components of the soil ecosystem (Brussaard, 1997; Coleman et al., 2012; Wurst et al., 2012). MNPs have been found to exert negatively effect on soil organisms through toxicity, causing physical damage, disruption of biological processes, and altering soil properties. MNPs release toxic substances, posing harm to delicate organisms such as microorganisms and worms. They disrupt essential biological processes, impacting growth, reproduction, and overall soil health. Additionally, MNPs alter soil properties, making it less suitable for certain organisms. These effects have cascading impacts on nutrient cycling, plant growth, and overall soil health, as depicted in Fig. 7. It is important to consider the physical, chemical, and nanoscale effects of MNPs, as well as their role as carriers and vectors of diseases, in order to comprehend the ecotoxicological effects of microplastics on soil animals.

4.2.2. Physical and chemical effects of micro- and nanoplastics on soil biota

MNPs have been found to have various physical effects on soil organisms. MNPs impact soil biota primarily through physical interactions (Cheng et al., 2021). Soil invertebrates can ingest microplastics, which can lead to blockages in their digestive systems or organ damage. Moreover, MNPs can adhere to the surface of soil microorganisms, thereby interfering with their normal metabolic functions (Dong et al., 2021). Moreover, MNPs can alter soil structure and nutrient availability, further affecting soil biota. MNPs reduce soil porosity, increase compaction, and hinder the availability of oxygen and water to soil organisms. Changes in soil nutrient availability due to MNPs can disrupt microbial activity and nutrient cycling in soil (Dong et al., 2021). In addition to physical effects, MNPs can also have chemical effects on soil organisms. MNPs contain additives, such as stabilizers, plasticizers, flame retardants, and colorants, which may leach out and pose environmental hazards (Gudeta et al., 2023; Khalid et al., 2021; Aurisano et al., 2021; Fantke and Illner, 2019), as showed in Table 3. Additionally, MNPs can absorb toxic pollutants from the environment, such as heavy metals and organic chemicals, potentially leading to their accumulating in the food chain.

NPs have a higher potential toxicity than MNPs due to their greater surface area per unit of mass. Moreover, NPs are more reactive and mobile, potentially leading to more widespread impacts (Yu et al., 2023). Limited research suggests that NPs can affect soil structure and microbial activity (Kim et al., 2023; Vaccari et al., 2022). Furthermore, MNPs can act as carriers of diseases and invasive species, thereby serving as a means for the spread of plant diseases (Gkoutselis et al., 2021). Additionally, MNPs can transport invasive species, like insect eggs or seeds, over long distances, leading to the establishment of new populations in previously unaffected areas.

In conclusion, MNPs have diverse effects on soil biota, including physical, chemical, and nano-level impacts, as well as implications for disease spread and invasive species. Despite research on these impacts is still being in its early stages, MNPs pose a growing concern for soil health and ecosystem functioning.

4.2.3. Ecotoxicological effects of micro- and nanoplastics on soil fauna

Soil fauna, which have food particle similar in size to MNPs, can be consumed by animals and have physiology toxic effects. It has been suggested by studies that MNPs can accumulate in the food chain, causing toxic effects on organisms across various trophic levels when

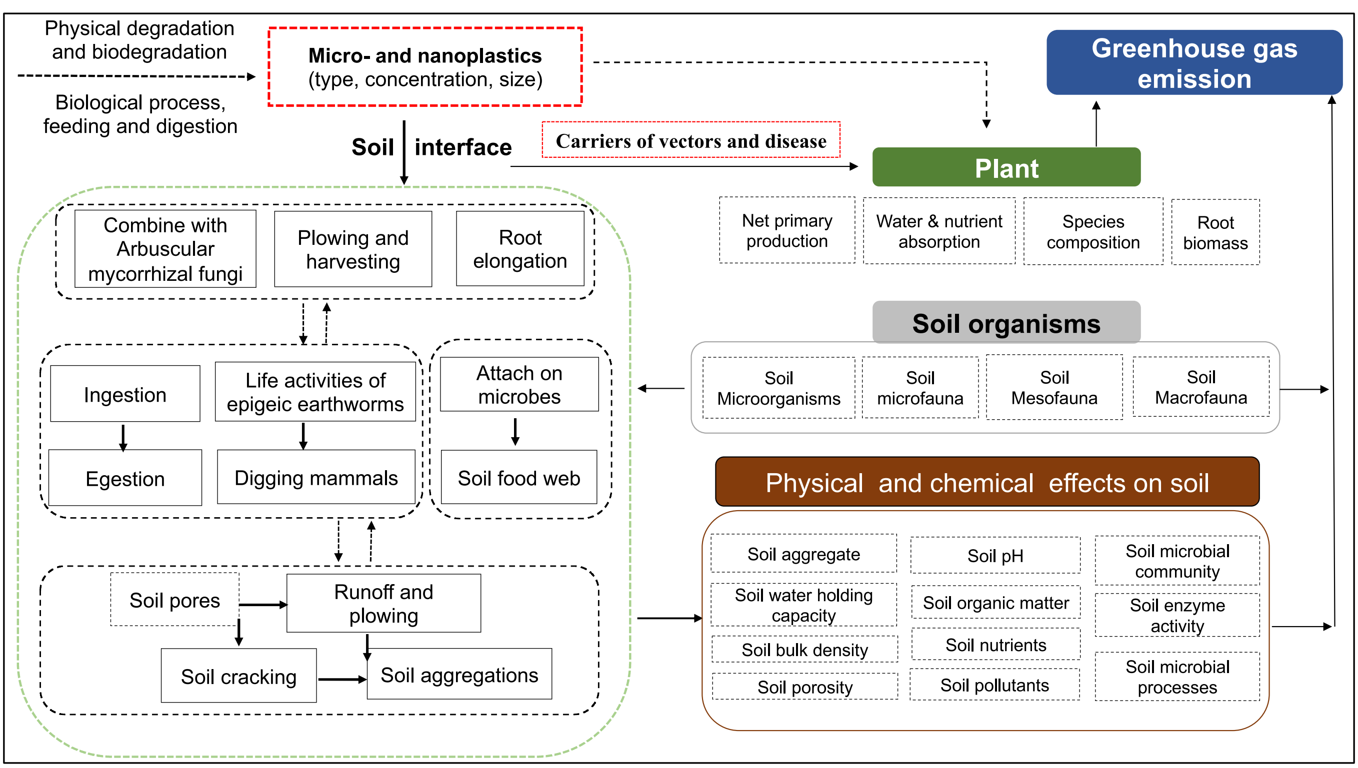

Fig. 7. Negative effects of micro- and nanoplastics on soil and its organisms.

Table 3
Types, representative compounds, functions and effects of example additives commonly used in micro- and nanoplastics.

Types of additives	Representative compounds	Plastic type	Function	Effects	References
Plasticisers	Phthalates	PVC	Makes plastics soft and bendable, enhances plastic ductility and plasticity.	Phthalates are endocrine disruptors and may affect fertility and development.	(Erkekoglu and Kocer-Gumusel, 2014; Wang et al., 2016)
Stabilisers	Lead, tin, calcium, and zinc stabilisers, etc.	PP, PE, ABS	Protects plastics from thermal decomposition and oxidation.	Lead is a neurotoxic agent and can cause neurological damage, especially in children. Tin compounds may also be toxic.	(Luo et al., 2022; Paganos et al., 2023)
Flame retardants	Polybrominated diphenyl ethers (PBDE) Hexabromocyclododecane, tetrabromobisphenol A	PS, PP	Improves the flame-retardant properties of plastics and reduces the risk of fire.	PBDE is toxic and may affect the reproductive and nervous systems of humans and animals.	(Taib et al., 2022; Wang et al., 2009)
Antioxidants	Bisphenol A, nonylphenol	PE, PP	Antioxidants can extend the life of plastics	Affects development and induces aberrations and endocrine disruptors	(Wang et al., 2022d; Yu et al., 2022)
Pigments	Polycyclic Azo (Mono- and Di-) etc.	PS, PLA, PVDE	Pigments can give plastics different colours	Some pigments may contain harmful substances such as heavy metals and need to be used with caution.	(Luo et al., 2022)

Notes: Acrylonitrile butadiene styrene (ABS); Polyvinylidene Difluoride (PVDF) and Polylactic Acid (PLA); Low density polyethylene (LDPE); Polyamides (PA); Polyethylene(PE); Polyvinyl chloride (PVC); Polybutylene terephthalate (PBT); Polybutylene adipate terephthalate (PBAT); Polystyrene(PS); Polyethene terephthalate (PET); Polymethyl methacrylate (PMMA); High-density polyethylene (HDPE); Polycarbonate (PC); Polypropylene (PP); Acrylonitrile-Butadiene-Styrene (ABS); Polyoxymethylene (POM); Polyurethane (PEU); Polybrominated diphenyl ether (PBDE); Polyurethane (PUR); Polyurethane foam (PUF).

exposed to high levels (Rillig, 2012). However, the investigation of soil animals is challenging due to factors such as their uneven distribution, diversity, size, diurnal and seasonal activity patterns. Earthworms have been extensively studied due to their abundance and their significant role in improving soil structure, water, and nutrient cycles. As a key model organism in soil ecosystems, earthworms are often selected to investigate the impact of various contaminants, including MNPs. Studies have revealed that the uptake rate of MNPs by earthworms increases with rinsing concentrations. Additionally, MNPs stimulate earthworms to produce amounts of intestinal mucus, leading to the growth of soil MNPs in the earthworm gut and affecting nutrient uptake through symbiotic relationships. On the other hand, MNPs concentrations of 28 %, 45 %, and 60 % w/w have a significant negative impact on earthworm growth and body weight, ultimately resulting in mortality (Lwanga et al., 2016). Similarly, Boots (2022) observed a decrease in earthworms body weight by an average of 3.1 % after 30-day exposure to MNPs. Conversely, some researchers examined the impact of 250–1,000 μm PE MNPs on the survival, growth, reproduction, histopathology, and immune system of Eisenia andrei earthworms using OECD artificial soil. The study revealed indications of pathological damage and immune system impacts (Rodriguez-Seijo et al., 2017). The presence of MNPs in the soil can initiate a chain reaction among soil organisms, potentially compromising the overall ecosystem stability.

MNPs have also been found to have toxicological effects on various soil organisms such as nematodes, hoppers, tail-hoppers, snails, mice, and isopods. Earthworms, nematodes, elasmobranchs, isopods and mites are among the most frequently studied soil animals (Chae and An, 2018). Table 3 reveals that MNPs can lead to intestinal damage, inflammation and immune response, neurotoxicity, alteration in the gut microbiota, liver dysfunction, weight loss, and decreased growth and reproductive rates of soil animals. Furthermore, Lwanga et al (Huerta Lwanga et al., 2017) observed the transfer of MNPs through the soil-earthworm-chicken food chain, with soil-to-earthworm feces and earthworm-to-chicken feces concentration factors of 12.7 and 105.0, respectively.

Studies examining the combined effects of MNPs and other contaminants on soil fauna are limited, with most research focusing on earthworms (Yao et al., 2020; Zeb et al., 2020). Experiments studies have demonstrated that the presence of MNPs in soil diminishes the survival rate of earthworms and impairs their capacity to decompose organic matter (Gudeta et al., 2023). Additionally, research has demonstrated that MNPs undergo gradual degrade in soil, producing smaller particles that are more readily ingested by soil animals, which consequently impact their physiological functions (Ding et al., 2022; Wang et al., 2022c). Furthermore, the co-contamination of MNPs and other pollutants might exacerbate the toxic effects on soil animals. For instance, experiments reveal that soil containing MNPs adsorb more organic pollutants, leading to higher toxicity levels (Mao et al., 2022). Similarly, studies have demonstrated that MNPs can modify the community structure of soil microorganisms, which subsequently affects the soil fauna's food chain (Lin et al., 2020; Wang et al., 2022c). However, Gaylor et al. (2013) exposed earthworms to polybrominated diphenyl ethers (PBDEs) alone and in combination with PBDEs, and the results indicated that the addition of MNPs did not significant affect the concentrations of PBDEs in earthworms.

The impact of MNPs on soil fauna is a multifaceted issue that necessitates consideration of various factors. These factors encompass the soil environment, biology traits of soil animals, chemical properties, type, and concentration of MNPs, other contaminants present, exposure duration, and the adsorption/desorption capacity of contaminants on the surface of MNPs (Ding et al., 2022; Yao et al., 2020). Moreover, the majority of studies investigating the impact of MNPs on soil fauna have been carried out in controlled laboratory settings (Wang et al., 2022c). These studies often employ fixed variables such as MNPs, contaminants, and organism types, along with short exposure durations and high concentrations that deviate significantly from the complexity of the natural environment. Future LCAI research must investigate the cumulative impact of combined MNPs contamination on the ecosystem, along with undertaking relevant ecological risk assessments. Therefore, a comprehensive analysis of the summary of the literature on MNPs on soil fauna and systematically summarized their ecotoxicological effects on earthworms, soil springtail, soil nematodes, soil megafauna and all specific data collected in **Table S1–S4**.

4.2.4. Ecotoxicological effects of micro- and nanoplastics on soil microorganism

Soil microorganisms play a crucial role in transformation and cycling of organic matter and nutrients in soils (Machado et al., 2018). Numerous studies have demonstrated that the introduction of MNPs to soil can influence soil enzyme activity, microbial biomass, microbial community structure, diversity, and other microbial-related properties. The magnitude of these effects is closely related to the type, particle size, concentration, and shape of the MNPs. Plastics can persist in soil ecosystems for extended periods, thereby modifying the composition of microbial communities (Fan et al., 2022; Zang et al., 2020). While many studies have examined the effects of MNPs on bacterial communities and diversity, the influence of PBAT MNPs at low levels was found to increase the diversity of soil bacterial communities relatively. In contrast, the physicochemical properties, bacterial community diversity and composition, and structure of soil were all affected by the addition levels of PBAT MNPs, demonstrating a significant correlation between bacterial community abundance and soil physicochemical properties in soils with different PBAT additions (Li et al., 2022c). Changes in microbial communities can, in turn, impact microbial functions, such as nitrogen and carbon cycling processes. MNPs represent a novel artificial ecological niche that is more compatible and attractive to microorganisms than soil, facilitating the recruitment of more bacteria for chemotactic selective colonization of their surfaces (Xie et al., 2021). This results in significant aggregation of bacterial and fungal communities in the soil. Plastic addition reduced the diversity of microbial communities, especially of soil bacteria, and influences the structure of the microbial community. In contrast, the addition of MNPs stimulates the growth of tolerant microorganisms (i.e., Nocardiaceae, Anaphylatoxigenic bacteria, Aeromonas) while inhibiting sensitive microorganisms (i.e., Helicobacter Nitrophilus, Aspergillus, Agrobacterium). This leads to the formation of specific microbial communities that potentially driving the evolution of soil microbial systems towards tolerant and degradative microbial species (Gao et al., 2021). Moreover, the presence of MNPs may further modify microbial ecological processes, such as carbon, nitrogen, and phosphorus cycling.

The addition of MNPs significantly increases soil CO_2 emissions, while having little effect on soil N_2O emissions (Gao et al., 2021). Recent studies investigating the effects of soil microeukaryotes and their functions have shown that high concentrations (1 %) of phenolic MNPs reduce the interactions between microorganisms and the contribution of stochastic processes, thereby altering the bacterial community composition. However, there is no significant effect on the composition of the eukaryotic microbial community. Soil N_2O release is significantly negatively correlated with functional genes related to nitrification processes, indicating that competitive relationships among microorganisms affect soil ecosystem N cycling processes. Additionally, it has been observed that the biomass of vegetables weakly decrease with the increase or decrease of MNPs, and this is significantly and positively correlated with the functional diversity of eukaryotic microorganisms and bacteria (Li et al., 2023b). Chen et al. (2020) found that MNPs affect the anaerobic denitrification process, which involves the conversion of nitrate and nitrite to gaseous forms of nitrogen, including nitrous oxide and nitrogen. This process occurs in the center of soil aggregates. Another study found that MNPs in the soil lead to an increase in the clumping of inter-rooted mycorrhizal fungi in plants, and these symbiotic fungi transport nutrients, including phosphorus, to their plant hosts, potentially affecting phosphorus cycling (Dong et al., 2021).

4.3. Management and mitigation of soil micro- and nanoplastics

The findings of bibliometric analysis have significant implications for policy and management strategies. They establish a foundation for evidence-based decision-making, informing the development of regulations, guidelines, and best practices for reducing plastic pollution in soils (Horton, 2022). As our understanding of the potential ecotoxicological effects of MNPs in soils deepens, the demand for effective management and mitigation strategies becomes crucial. The dispersion of MNPs in soil environments can result from various sources, including agricultural practices, wastewater sludge application, and the degradation of larger plastic items. These contaminants not only pose potential risks to the physical structure of the soil but also to its biota. Therefore, effective management strategies should encompass measures to reduce plastic waste generation, promote sustainable agricultural practices, and improve waste management systems to prevent plastic contamination of soils. This section provides an overview of current management strategies and proposes new mitigation approaches based on recent research findings.

4.3.1. Current management strategies: Existing strategies and measures

Addressing the pervasive issue of MNPs in soils necessitates a multifaceted approach that encompassing both immediate containment measures and long-term preventive strategies. In areas with high concentrations of MNPs, immediate containment becomes paramount. Physical barriers, like geotextiles, offer effective solutions in these cases as they prevent the migration of MNPs to neighboring regions and reduce the potential for broader environmental contamination. Concurrently, innovative biological methods, such as bioremediation, have begun to gain traction. Preliminary studies have illuminated the potential of specific fungi and bacteria to degrade plastics. While these methods have predominantly been explored for larger plastic debris, with ongoing research, adaptation of this strategy to target MNPs seems a promising avenue.

Nevertheless, while technological and biological solutions are vital, they must be supported by robust regulatory frameworks. Recognizing the detrimental impacts of plastics on soil health, many nations are moving towards the formulation and implementation of regulations. These are designed to not only limit plastic utilization in agricultural practices but also to curtail plastic waste generation at large. Complementing these regulatory efforts, public awareness campaigns play an indispensable role. By enlightening both the general population and specific industrial sectors about the consequences of unmanaged plastic waste, these campaigns foster more responsible behaviors, thereby mitigating the influx of plastics into our environment.

4.3.2. Recommended mitigation approaches: New methods and strategies based on the research

The increasing concern surrounding the presence of MNPs in soils has prompted the associated ecotoxicological and development of innovative strategies to address their dispersion and the associated ecotoxicological effects. One significant source of MNPs in soils is wastewater sludge. By enhancing the filtration processes within wastewater treatment plants, the load of MNPs in the resultant sludge applied to fields can be substantially diminished. In addition to direct intervention methods, such as advanced filtration, certain soil amendments have been recognized for their ability to immobilize MNPs. For instance, recent studies have indicated that biochar, a carbon-rich byproduct of pyrolysis, demonstrates a notable capacity for adsorbing microplastics. This adsorption capability reduces their movement within soils and mitigates their bioavailability and potential toxic effects.

Beyond direct mitigation strategies, it's imperative to reassess our production and consumption habits. The principles of the circular economy emphasize designing products for recycling or biodegradation, which, if widely adopted, can greatly reduce plastic waste. In the agriculture context, promoting the use of biodegradable plastics can significantly decrease the introduction of MNPs into soils, marking a crucial shift toward sustainable farming. Looking forwards, the realm of nanotechnology holds promise. Preliminary research suggests the potential of novel nanomaterials specifically designed to target and extract MNPs from soils. Although still in its early stages, the successful implementation of this approach could revolutionize MNPs management in soil ecosystems.

5. Future directions in soil MNPs research

Despite the growth in research on soil MNPs pollution, several knowledge gaps remain. Future studies should prioritize long-term monitoring of plastic accumulation in soils, elucidating the mechanisms of plastic uptake and transport within soil ecosystems, and assessing the potential risks to human health through the food chain (Ding et al., 2022; Tian et al., 2022). Additionally, interdisciplinary collaborations and integration with other fields, such as soil science, ecotoxicology, and environmental engineering, can provide valuable insights and facilitate the development of holistic approaches to tackle this issue. Long-term monitoring is essential to understand the dynamics and temporal trends of plastic accumulation in different soil types and under various environmental conditions (Steinmetz et al., 2016). This requires the development and standardization of robust, sensitive, and cost-effective methods for plastic quantification and characterization in soils. The mechanisms of plastic uptake and transport within soil ecosystems are still not fully understood. Unravelling these mechanisms can provide insights into the fate of plastics in soils, their interaction with soil biota, and their potential impacts on ecosystem services (Huang et al., 2022). Key areas of focus should include the effects of soil properties, climate conditions, and biological activities on plastic behavior in soils (de Souza Machado et al., 2018).

The potential risks to human health through the food chain are a pressing concern (Al Mamun et al., 2023). Due to the possibility of plastics accumulation in crops and livestock, there are potential risks of plastic transfer to humans through food consumption(Allouzi et al., 2021). Further research is required to comprehend this process and its implications for human health, particularly focusing on the potential effects of chronic exposure to plastic-derived contaminants (Al Mamun et al., 2023; Sharma and Chatterjee, 2017). Moreover, valuable insights can be gained through interdisciplinary collaborations and integration with other fields, such as soil science, ecotoxicology, and environmental engineering (Chang et al., 2022). The complexity of pollution from soil MNPs necessitates a holistic approach that combines expertise from various fields. This approach can promote the development of comprehensive mitigation strategies, which can encompass plastic waste reduction, management, and soil remediation techniques. Moreover, greater emphasis should be given to socio-economic studies concerning pollution from soil MNPs. Comprehensive understanding of the economic costs, policy implications, and societal perceptions of plastic pollution in soils is key to generating meaningful change and promoting sustainable practices. Lastly, there is an urgent need for policy-oriented research to guide the formulation of regulations and guidelines for addressing plastic pollution in soil. By bridging the gap between science and policy, research can play a crucial role in shaping effective and informed strategies to tackle the issue of soil MNPs pollution. The connection between plastic pollution and planetary boundaries reveals a close link to the soil ecosystem and the overall ecological balance of our planet (Persson et al., 2022; Carney Almroth et al., 2022). By uncovering the potential impacts of microplastics on factors like soil biodiversity and nitrogen cycling, we recognize the need for extensive methodological advancements in this emerging field. Subsequent research should concentrate on filling this knowledge gap, enabling a better understanding and management of the potential challenges presented by plastic pollution in relation to planetary boundaries.

6. Conclusion

Soil MNPs pollution research is a rapidly growing and critical field that has profound implications for soil health, biodiversity, and ecosystem functionality. The number of publications related to soil MNPs pollution has steadily increased over time, indicating a growing interest. The geographical distribution of research shows that regions with high plastic consuming and producing, such as Europe, North America, and East Asia, are at the forefront of this field.

This study also identified collaborative networks among researchers and institutions, emphasizing interdisciplinary collaborations and knowledge exchanges across regions are crucial. An examination of research themes and keywords provided insights into key areas in the field, highlighted the urgency of understanding the sources, distribution, and impacts of MNPs on soil ecosystems. Emerging research fronts, such as the ecotoxicology of microplastics and plastic degradation in soil, indicate the necessity for further investigations to gain a better understanding of the ecological impacts and degradation processes of plastic particles in soil. This study also identified the future research directions, long-term monitoring of plastic accumulation in soils, understanding plastic uptake and transport mechanisms, and evaluating human health risks. Addressing these gaps would aid in developing effective mitigation strategies and shaping evidence-based policies to reduce plastic pollution in soil.

In conclusion, the bibliometric analysis has yielded valuable insights into the research landscape, trends, and knowledge domains in the field of soil MNPs pollution. This finding of study contributes to the expanding knowledge base on this issue, establishing a cornerstone for future research, policy development, and management strategies aimed at mitigating the environmental impacts of soil plastic pollution. Therefore, it is crucial to sustain research efforts, foster interdisciplinary collaborations, and implement sustainable practices to preserve soil health and uphold the integrity of terrestrial ecosystem.

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CRediT authorship contribution statement

Hongdou Liu: Data curation, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Lizhen Cui:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Tong Li:** Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft. **Calogero Schillaci:** Data curation, Review & editing. **Xiufang Song:** Writing – review & editing. **Paolo Pastorino:** Data curation, Review & editing. **Hongtao Zou:** Data curation, Review & editing. **Xiaoyong Cui:** Funding acquisition, Investigation, Supervision, Writing – review & editing. **Zhihong Xu:** Investigation, Methodology, Writing – review & editing. **Peter Fantke:** Conceptualization, Funding acquisition, Supervision, Methodology.

Declaration of Competing Interest

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

Data availability

Data will be made available on request by the first author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111109.

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