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Trends and mechanisms in agricultural mulch film microplastic pollution: a critical review. Review article.

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This study systematically reviews the formation, migration, and effects of mulch film-derived microplastics on soil ecosystems, as well as the combined effects of microplastics and pesticides. This review highlights that mulch film microplastics affect plant growth by altering soil properties, nitrogen metabolism, and photosynthesis. Additionally, microplastics have negative effects on animal growth, behavior, reproduction, and tissue integrity, with potential health risks to humans through food chain contamination. The migration of microplastics in soil is influenced by biotic and abiotic processes, that common soil organisms accelerate the dispersal of microplastics through bioturbation. The interaction between microplastics and pesticides was evaluated, revealing potential risks of enhanced soil pollution through changes in pesticide adsorption, degradation, and transport. Future research should prioritize the development of biodegradable mulch films, improvements in microplastic degradation technologies, and investigations into the environmental behavior of microplastics in soil to mitigate their ecological impacts and support sustainable agricultural practices.

Keywords: Microplastics; Mulch Film; Soil Pollution; Migration.

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INTRODUCTION

Agricultural mulch films regulate soil temperature, suppress weed growth, and prevent water loss, thereby enhancing water use efficiency and increasing crop yields, leading to greater profitability[1]. Traditional agricultural mulch films are primarily composed of polyethylene (PE) and polyvinyl chloride (PVC)[2]. Agricultural plastic film is one of the main sources of microplastics in the soil.

Although plastic mulch technology has brought advantages to agricultural development, its widespread use and difficulty in degradation have led to significant residual pollution, causing the application of mulch film technology to evolve from a "white revolution" into "white pollution"[3]. Given that agricultural land is closely linked to the survival of plants and animals and the safety and health of human food[4], the issue of microplastic pollution from agricultural mulch films has become a pressing concern.

Traditional agricultural mulch films are difficult to degrade and recycle. Due to mechanical wear and weathering from long-term agricultural practices, as well as factors like high-intensity UV radiation[5] and natural rainfall[6], the performance and structure of mulch films can change, causing them to break down into small fragments that enter the soil. Frequent use of agricultural mulch films has led to the accumulation of microplastics in the soil, which impacts soil health and the diversity of soil microbial communities[5], and ultimately affects crop growth and agricultural productivity[7].

Researchers such as using dye tracers to track soil moisture movement and measure the dynamic behavior of soil physical properties and water transport in the top 20 cm of cultivated soil[8]. Their study confirmed that microplastic residues from agricultural mulch films could alter soil properties like moisture content, soil permeability (KS), porosity, and bulk density (ϱb). In addition to physical properties, Plastic residues from agricultural films (0–100 cm^2) could also alter soil pH and organic matter content, leading to soil quality degradation[9]. Also, residual agricultural mulch films can reduce soil permeability, inhibit water movement in the soil, and easily adhere to plant surfaces, hindering nutrient and water absorption through plant roots and affecting plant growth[7]. Some studies have shown that agricultural plastic residues in soil reduce crop yields by an average of 16.10%[10]. Soil plastic fragments also decrease microbial diversity[11] and enzyme activity[12], and affect the metabolic functions of soil microbial communities, impacting fundamental cellular processes[13, 14]. Due to transpiration pull or cracks at lateral root emergence sites, mulch film fragments can enter plants and, through the food chain, lead to the accumulation of microplastics in animals, posing risks to food safety and human health[15].

Many researchers have systematically studied the pollution issues caused by agricultural mulch films. Zacharias Steinmetz and others evaluated the sustainability of agricultural mulch films from various disciplinary and societal perspectives[16], discussing the economic benefits and environmental pollution associated with mulch films. Brenda Madrid and colleagues described the application and disposal methods of agricultural mulch films in their country, as well as the feasibility and limitations of biodegradable films[17]. Currently, traditional mulch films are gradually being replaced by biodegradable ones, and more scholars are conducting in-depth research on biodegradable films[18]. Although biodegradable mulch films aim to degrade into environmentally less harmful substances under microbial conditions[19], the complexity of the degradation process and whether the resulting products pose other environmental risks are current research focuses[20, 21]. The novelty of this paper lies in the introduction of bibliometric methods. Compared with traditional reviews, it provides more comprehensive data support and trend prediction, offering a better understanding of current research hotspots and directions.

The paper conducts a detailed analysis of both biotic and abiotic factors influencing the migration of microplastics in soil and further discusses the contributions of micro-arthropods and burrowing mammals to soil microplastic migration, expanding beyond the common focus on earthworms and other animals. Additionally, the paper explores the combined effects of pesticides and mulch-derived microplastics, an interdisciplinary research direction rarely addressed in previous reviews. The potential of biodegradable mulch films as a future research hotspot is also emphasized, providing a new perspective on the issue of microplastic pollution from agricultural mulch films. Moreover, the paper offers valuable suggestions for future research in this field.

MATERIALS AND METHODS

Research Methodology

Bibliometrics, a cross-disciplinary research method that quantitatively analyzes all knowledge carriers through information science, mathematics, statistics, and other techniques, has been used to analyze research hotspots and development trends in specific disciplines or fields, to provide a more comprehensive understanding of the research area. Bibliometric visualization helps to intuitively understand and describe the results of bibliometric analyses. Visualization can transform large amounts of bibliometric data into graphs and other forms, making the data easier to understand and compare, and providing more comprehensive and in-depth analytical results.

In this study, VOSviewer and Citespace, two commonly used bibliometric tools for knowledge mapping, were used to create images and charts. VOSviewer is primarily used for the visualization of co-citation networks, facilitating the processing of large-scale bibliometric data and clearly displaying the relationships between documents. It can also be used for heat maps, cluster analysis, and more.

Data Retrieval

The literature data used in this study were obtained from the Web of Science database, a comprehensive academic information platform covering most disciplines with authoritative and high-impact resources.

To ensure comprehensive and accurate data retrieval, we selected the SCI-EXPANDED and SSCI databases as the search sources. The search conditions were defined as: TS = (Agricultural OR cropland OR farmland OR land OR ground OR soil OR field OR farm OR arable land OR peasant farm) AND TS = ("mulch films" OR "plastic mulching" OR "plastic film" OR "plastic films" OR film OR films OR "plastic mulch film" OR "mulch film" OR "mulching film" OR "foil" OR "wrap" OR "membrane" OR "sheeting") AND TS = (Microplastics OR Microplastic OR MP OR MPS). The time span was set from 2013 to 2023. The document types included research articles (Article) and review articles (Review Article), excluding unrelated categories such as medicine, radiology, and applied mathematics. However, studies related to environmental toxicology, public health, and the effects of microplastics on human health were retained due to their relevance to the ecological and food chain impacts of agricultural microplastic pollution. A total of 844 papers were retrieved. After a first round of keyword filtering, an additional manual screening was conducted by reading the titles and abstracts to exclude irrelevant papers. In the end, 325 papers (including 275 research articles and 50 review articles) were retained for analysis. The 325 papers used in this study came from 52 countries, 491 institutions, and 1,544 authors, published in 99 journals, and cited 11,565 references from 3,125 journals.

Price's Law was applied to analyze the authors of publications, not only to determine the number of core authors in a particular research area, but also to understand the core research strength within the field. The renowned scholar Price proposed that within a given topic, half of the papers are written by a group of highly productive authors, whose number is approximately equal to the square root of the total number of authors (Price, 1963).

$$\sum_{m+1}^{I} n(x) = \sqrt{N}$$

In the formula, *n(x)* represents the number of authors who have written *x* papers, and $I = nmax$ represents the number of papers published by the most productive author in a given period within the field. According to VOS viewer data, the maximum number of publications by a single author in this field (*nmax*) is 15, and *N* is the total number of authors in the field. To qualify as core authors, the standard requires that the publications of authors with more than m papers account for half of the total publications. Based on the Price's Law formula: $0.749 \times \sqrt{n_{max}} \approx 2.901$, so authors with three or more publications are considered core authors in this field.

RESULTS AND DISCUSSION

Trend Analysis of the Number of Publications

By analyzing the annual number of publications in the field of agricultural film microplastics, the resulting trend chart allows to clearly observe the changes in annual number of publications. This enables predictive analysis of future development trends and shifts in research hotspots within the field. Fig. 1 shows the annual number of publications in the field of agricultural film microplastics from 2013 to 2023, along with its percentage of each year's contributions to the total publications. The number of publications in this field was quite low from 2013 to 2018. In 2016, plastic mulching in agriculture had already become a globally applied agricultural practice due to its immediate economic benefits[16]. However, the sustainability of plastic mulching from environmental and agronomic perspectives remained unclear[22]. During this period, the issue of pollution caused by residual plastic mulch started to gain attention, and China entered a new phase of technological upgrades in agricultural plastic mulch.

Around 2018, as plastic-related environmental pollution became increasingly severe, a global wave of plastic bans emerged. On January 11, 2018, the UK Prime Minister unveiled the country's 25-year environmental strategy in London, announcing plans to eliminate all avoidable plastic waste by 2042. The strategy also emphasized significantly reducing, and where possible, preventing all forms

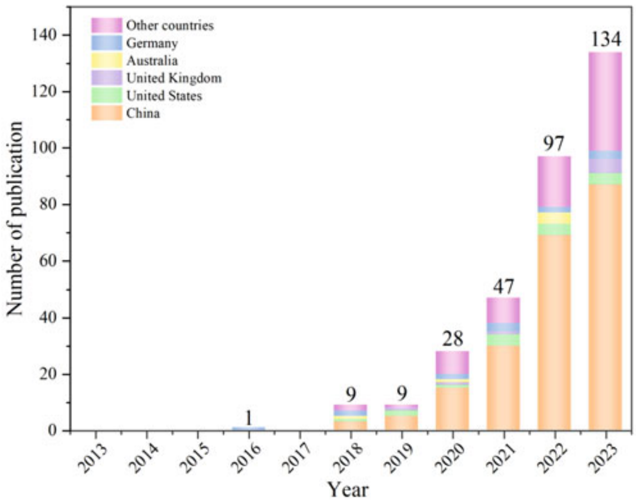

Figure 1. Preparation process of artificial cracks

of marine plastic pollution, particularly those originating from land-based sources. This comprehensive policy is detailed in the official document "A Green Future: Our 25 Year Plan to Improve the Environment[23]". In May 2018, the European Commission proposed "Single-use plastics: New EU rules to reduce marine litter". This directive targeted single-use plastic products by banning the sale of items for which sustainable alternatives already existed, such as cotton buds, cutlery and straws, and promoted the use of eco-friendly substitutes. Member states were required to establish consumption reduction targets for plastic food containers and beverage cups, and to prohibit the free distribution of such products. The directive also mandated that producers bear the costs of waste management and public awareness for products like food packaging, beverage containers, and cigarette butts, while encouraging the development of greener alternatives. Furthermore, it set a binding target for EU member states to achieve a 90% collection rate for plastic bottles by 2025 and introduced mandatory labeling on sanitary products and wet wipes to inform consumers about disposal methods and environmental risks. Public education campaigns were also emphasized to enhance awareness of plastic pollution and sustainable waste management[24]. In August 2018, South Korea's Ministry of Environment issued a 40-day legislative notice for proposed amendments to the "Act on the Promotion of Saving and Recycling of Resources", aiming to further curb the use of single-use plastic bags. While large supermarkets and retailers had already been prohibited from providing such bags free of charge, the revised regulations expanded the ban to include confectionery shops and other food service businesses, prohibiting them from offering disposable shopping bags free of charge as well. The amended law officially came into effect on January 1, 2019, marking a nationwide ban on the free distribution of single-use plastic bags in commercial settings[25]. Many countries began researching degradable and renewable plastics to replace single-use plastic products or issued bans prohibiting their use. The theme for World Environment Day 2018 was "Beat Plastic Pollution", calling for global efforts to combat single-use plastic pollution, which had become pervasive. In mid-December 2017, China released the mandatory national standard "Polyethylene Blown Agricultural Mulch Film", which came into effect on May 1, 2018. This new national standard is significant for reducing the "White Pollution" in farmland and improving soil and environmental quality[26]. As a result, since 2018, the annual publication count has shown a significant upward trend as more scholars and researchers joined the field, leading to a growing research community. In 2022 and 2023, the number of publications stabilized at around 100 per year, with 2023 seeing the highest number of publications at 134 papers. This indicates that with the continuous development of society and economy and the widespread use of agricultural plastic mulch, the demand for environmental and economic benefits is increasing. It can be inferred that research in this field will continue to grow in the future.

Analysis of the Relation of Literatures

Analysis of Source Journals on This Topic

To understand the landscape of research journals in the field of agricultural plastic mulch microplastics, relevant data retrieved from the Web of Science database were analyzed. The top three journals are "Science of The Total Environment" with 121 publications, "Journal of Hazardous Materials" with 64 publications, and "Environment Pollution" with 50 publications. The journal with the highest number of publications, "Science of The Total Environment," is an international multidisciplinary journal that publishes research on the entire environment. It covers a wide range of research topics, including the environmental impacts of climate change, agriculture, forestry, and land use. According to the Journal Citation Reports (JCR), Science of the Total Environment, Journal of Hazardous Materials, and Environmental Pollution have consistently ranked in the top quartile (Q1) of the "Environmental Sciences" category over the past decade (2013–2023). In 2023, Science of the Total Environment had an impact factor of 8.2, ranking 31st among 358 journals in the environmental sciences field. Journal of Hazardous Materials had an impact factor of 12.2, ranking 12th, while Environmental Pollution had an impact factor of 7.6, ranking 37th out of the same 358 journals[27]. These journals provide valuable references for future researchers and lay the foundation for further in-depth studies in the field, thereby promoting its development.

Author Analysis on This Topic

A total of 122 core authors were identified, contributing a total of 488 papers, indicating that a relatively stable core author group has formed in the field of agricultural plastic mulch microplastics. Table 1 presents the top ten high-productivity core authors in this field. The author with the highest number of publications is Davey L. Jones, who published 15 papers between 2013 and 2023, with 1,090 citations and an average of 72 citations per paper. The second-ranked author is Violette Geissen, with 10 publications, 1,842 citations, and an average of about 184 citations per paper, making her the author with the highest average citations per paper. Davey L. Jones is a professor of environmental science and public health at Bangor University and a professor of soil science at Murdoch University in Western Australia,

Table 1. The top ten highly productive core authors ranked by the number of publications

Rank	Author	Number of Publications	Citations	Average Citations per Paper
1	Jones, Davey L.	15	1090	72
2	Geissen, Violette.	10	1842	184
3	Huang, Yi.	10	1386	138
4	Flury, Markus	9	1075	119
5	Yan, Changrong	9	265	29
6	Liu, Qin.	9	310	34
7	Yang, Xiaoming.	8	1009	126
8	Jia, Weiqian.	8	1012	126
9	Wang, Jie.	7	636	90
10	Hayes, Douglas G.	7	1079	154

mainly researching microplastic pollution soil microbial diversity[28], and ecosystem functions[29]. Violette Geissen is a professor at the Environmental Science Department of Wageningen University in the Netherlands, focusing on environmental assessment and management, pollution monitoring and control[30], and microplastics[31]. Both have shown a high level of interest in this field of research.

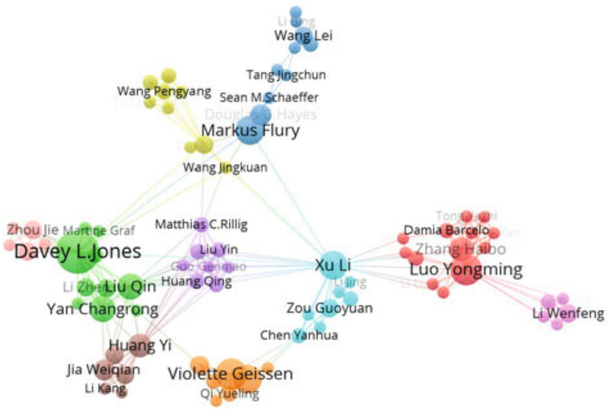

Figure 2. Author collaboration co-occurrence network

A total of 122 authors with more than three co-authored publications were identified through VOSviewer analysis, shown in Fig. 2. There are five main clusters. From Table 2, it can be seen that Cluster 1 primarily consists of scholars such as Jones Davey L., Yan Changrong, and Liu Qin. This group primarily collaborates on research related to the impact of microplastic residues from agricultural plastic mulching on soil properties by altering the physical structure of the soil. They explored the distribution and migration of microplastics in soil[32], quantified the accumulation of plastics in soil after long--term continuous use of plastic film under UV conditions[4], and studied the abundance of macro- and microplastics in soil[33]. They also summarized the effects of plastic mulch on soil and plant growth under different driving factors, noting that plastic residues can be absorbed by the roots of plants in contaminated soils and deposited into the above-ground parts of plants[34]. Additionally, they researched the uncertainties of using biodegradable mulch as an alternative to traditional plastic mulch, noting that biodegradable mulches, designed to degrade more quickly, may generate more microplastic pollution in the short term compared to traditional plastics and affect soil nutrient cycling and soil quality[21].

Cluster 2 is primarily represented by authors such as Luo Yongming, Zhang Haibo, and Barcelo Damia. This group focused on the correlation between microplastics from plastic mulch and phthalates in the soil, as well as the activity of soil microorganisms. Traditional plastic films contain about 20–60% phthalates[35], This group found that phthalate levels increase with the amount of plastic residue in the soil, while microbial carbon and nitrogen, enzyme activity, and microbial diversity decrease significantly[36]. They empirically estimated that pollution levels in most Chinese agricultural soils are very high and strongly correlated with management practices (recovery and non-recovery) after plastic film

Table 2. Top Five Cluster Representative Authors

Cluster	Colour	Author
1		Davey L. Jones, Li Zhen, Liu Qin, Yan Changrong, David R. Chadwick, Qi Ruimin, Zang Huadong.
2		Damia Barcelo, He Defu, Li Wenfeng, Luo Yongming, Pan Xiangliang, Zhang Haibo.
3		Nicolas Beriot, Violette Geissen, Qi Yueling, Yang Xiaomei,Esperanza, Huerta Lwanga.
4		Xu Li, Chen Yanhua,Jin Tuo, Li Jing, Liu Dongsheng, Wang Xuexia, Zhang Jiajia, Zou Guoyuan.
5		Markus Flury, Li Bing, Douglas G. Hayes, Sean M. Schaeffer, Sun Hongwen, Tang Jingchun, Wang Jun, Wang Lan, Wang Lei, Zhang Ying.

application[35]. The group also explored the negative impacts of different plastic mulch residues on soil physical properties, crop growth, and the introduction of harmful pollutants into the soil, potentially affecting ecosystem and human health[37].

Cluster 3 is primarily represented by authors such as Geissen Violette, Yang Xiaomei, and Qi Yueling. Their research examined the impact of agricultural plastic debris on soil properties, demonstrating that the type, size, and amount of plastic debris, as well as the interactions between these factors, play complex roles in altering measured soil parameters[38]. They also investigated the effects of residues from traditional and biodegradable mulches on soil suppression, plant (wheat) rhizosphere, and microbial communities[39], finding that both agricultural and biodegradable mulch residues significantly influence wheat growth, rhizosphere bacterial community composition and structure, rhizosphere volatile distribution, and soil chemical properties. Compared to traditional plastic mulch, biodegradable mulch has a more pronounced negative impact on wheat growth[7]. Further, their studies showed that adding plastic mulch residues to suppressive soil had no significant impact on disease symptoms in Fusarium-infected wheat or on the composition, structure, and diversity of plant-associated bacterial and fungal communities[14].

Cluster 4 is primarily represented by authors such as Xu Li, Chen Yanhua, and Zou Guoyuan. Their collaborative research summarized the pollution distribution patterns caused by microplastics in long-term cultivated soils across China, providing a scientific basis for the rational use and management of plastic mulch and for addressing soil microplastic pollution[40]. They also conducted comparative studies between farmland soils with long-term plastic film mulching and soils without mulching, finding that prolonged plastic film mulching increases microplastic pollution in agricultural soils[41, 42]. Additionally, their research determined that sandy soils have higher microplastic abundance compared to grassland and forest soils, and that microplastic distribution varies during soil recovery under different vegetation covers, with Pinus tabulaeformis having the highest microplastic concentration and jujube trees the lowes *t*[43].

Cluster 5 is composed of scholars such as Markus Flury, Douglas G. Hayes, and Tang Jingchun. This group focuses on biodegradable mulch films, initially questioning whether they can resolve the plastic pollution issues associated with agricultural mulching. They pointed out that incomplete degradation of biodegradable plastics could lead to the accumulation of plastic fragments in the soil[44]. Using the quartering method, they accurately estimated mulch application rates, finding that even with repeated use, biodegradable mulch films degrade over time in the field without accumulating in farmland, although complete degradation generally takes more than a year[45]. They also tested the impact of different types of biodegradable and traditional mulches on soil functional characteristics and health indicators, concluding that biodegradable mulches have the potential to replace traditional mulches but require long-term experimental evaluation[46, 47]. Their research also showed that biodegradable mulches provide soil moisture dynamics comparable to traditional mulches[48] and similar quality in crop yields[49].

A cluster led by authors like Huang Yi, Jia Weiqian, and Li Kang focused on the impact of biodegradable plastic mulch and traditional plastic mulch on soil microbial community network structure and function[50, 51]. While much research on microplastic rings has focused on bacterial communities, this cluster found that the diversity and composition of fungal communities in biodegradable microplastic rings are significantly reduced[52]. Other studies suggest that microplastics can alter soil fungal communities and potentially impact biogeochemical cycles[51]. They also conducted a comprehensive assessment of the potential risks associated with plastic layers of different mulches[53]. Furthermore, scholars like Huang Qing and Lin Yin reviewed the human or environmental factors influencing the distribution of microplastics in Chinese soils, providing models for assessing and controlling plastic pollution in natural soil environments[54].

Country Distribution Analysis

An analysis was conducted on the publication output from 52 countries to identify the leading contributors to research on agricultural plastic film microplastics. Visualization was performed using VOSviewer, focusing on countries with three or more publications. The results are illustrated in Fig. 3, which shows the network of countries based on their publication output. Larger circles represent countries with a higher number of publications. Different colors of circles indicate different clusters. Lines between circles represent collaboration strength, with thicker lines indicating more frequent co--authored publications. The analysis reveals a prominent top-heavy distribution, with China and the United States being the primary contributors. The overall distribution of countries is uneven.

From the global map and country distribution, it is evident that there are 21 countries collaborating with China, with the United States being the closest collaborator. In 2023, China and the United States jointly published the "Sino-US Sunny Land Declaration on Strengthening Cooperation to Address the Climate Crisis," emphasizing cooperation on circular economy and resource efficiency and committing to ending plastic pollution. The collaboration between the U.S. and Pakistan within the same cluster indicates a shared focus on research areas, while the U.K. and Australia also belong to the same cluster with close cooperation. Germany collaborates with many developed countries, with Canada being a particularly

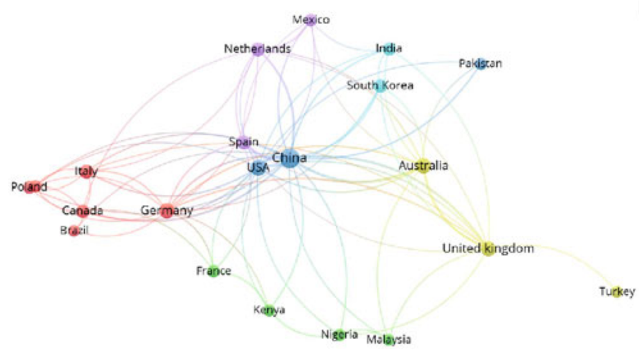

Figure 3. Publication Country Cluster Distribution Network

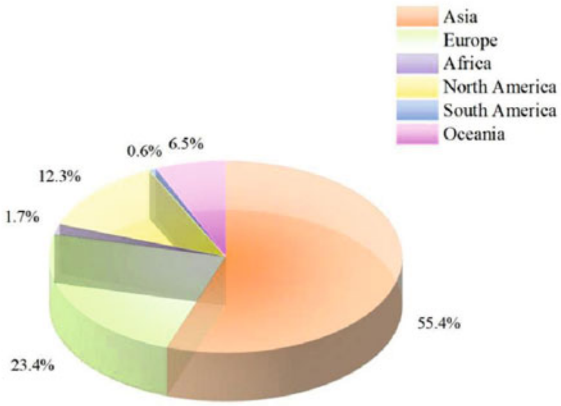

Figure 4. Distribution Proportion of Countries Collaborating with China Across Six Continents

close partner. Fig 4 shows the distribution of countries collaborating with China across six continents.

Table 3 reveals that Asia leads in the number of publications on agricultural plastic film microplastics, with a total of 255 publications. Europe follows with 106 publications. North America, primarily driven by the U.S., has a total of 57 publications, including contributions from Canada and Mexico. This indicates that the environmental pollution issues related to agricultural plastic film microplastics are significant concerns in Asia, Europe, and North America. China, with 227 publications, as the largest producer and user of agricultural plastic films in Asia and globally, faced a substantial challenge with plastic film residue pollution, with 2018 consumption reaching 2.5 million tons, accounting for over 70% of Asia's and nearly 50% of the global usage.

Institutional Analysis

The analysis of 325 papers shows contributions from 491 institutions. VOSviewer identified the top ten institutions based on the number of publications, shown in Table 4. The Chinese Academy of Sciences (Chinese Acad Sci) is the leading institution with 44 publications, followed by Northwest A&F University with 27 publications. Wageningen UniversityResearch, with the highest average citation per paper of 147, stands out for its prestigious reputation in ecology, agricultural science, and environmental science globally, and is considered a top institution in agriculture and environmental science research.

Citation Analysis

The literature was filtered to include only those cited at least 50 times, resulting in a selection of 33 papers. The relationships among these papers are illustrated in the accompanying figure. From Fig. 5, it is evident that highly co-cited papers in this field can be categorized into three clusters. The red cluster primarily focuses on the accumulation and migration characteristics of microplastics in agricultural soils. It examines the increasing concentration of microplastics in soil and measures microplastic particles in organisms such as earthworms. Research data indicate that soil microplastics can enter terrestrial food webs[55]. The green cluster is more oriented towards studying the various impacts of agricultural microplastics on soil ecosystems[56], including the physicochemical properties of the soil itself[57], and the effects on soil flora and fauna[58] as well as microbial communities[59]. The blue cluster mostly consists of review articles on agricultural plastic film microplastics, systematically describing various issues related to this field[60].

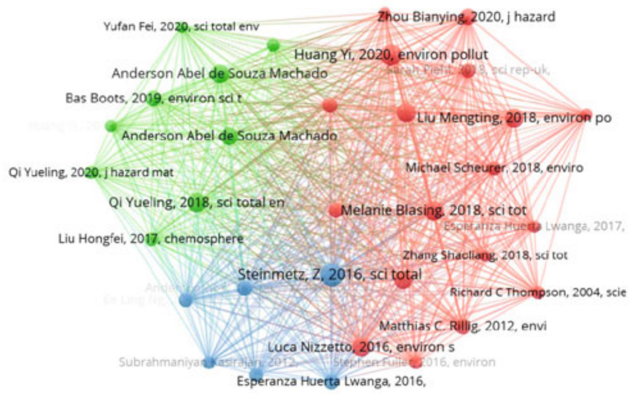

Figure 5. Citation Analysis Network

The most cited article, as shown in Table 5, with 126 citations, discusses the short-term benefits and long-term environmental pollution issues of plastic film cover, emphasizing the accumulation of microplastic debris in soils and potential soil degradation over time[22]. The second most cited article conducted an extensive investigation of plastic concentrations in soil samples from 19 provinces in China, revealing that mulch films are likely the primary source of both macroplastics and microplastics in the soil[61]. The third most cited article focused on methods for quantifying and identifying microplastics in soil and pointed out that agricultural irrigation and soil amendments might be major sources of microplastics in soil[62].

Table 3. Publication Count and Collaborating Countries Across Six Continents

Continent	Collaborating Countries	Number of Collaborative Publications
Asia	China (227), India (8), Turkey (3), Malaysia (3), South Korea (10), Pakistan (4)	255
Europe	United Kingdom (25), Spain (14), Netherlands (15), Germany (23), Italy (16), Poland (4), Sweden (3), France (6)	106
North America	United States (42), Mexico (6), Canada (9)	57
Oceania	Australia (30)	30
Africa	Kenya (4), Nigeria (4)	8
South America	Brazil (3)	3

Table 4. Top Ten Institutions by Number of Publications

Research Institution	Number of Publications	Citations	Average Citations per Paper
Chinese Acad Sci	44	2266	51
Northwest A&F University	27	1205	44
Minist AgrRural Affairs	21	1072	51
China Agricultural University	21	791	37
university of chinese academy of sciences	18	900	50
Chinese Acad Agr Sci	16	1273	79
Bangor University	15	1090	72
University of Western Australia	13	962	74
Beijing Acad AgrForestry Sci	13	289	22
Wageningen UniversityResearch	12	1765	147

Table 5. Top Ten Papers by Co-Citation

Title	Year	Citations
Plastic mulching in agriculture. Trading short -term agronomic benefits for long -term soil degradation?	2016	126
Agricultural plastic mulching as a source of microplastics in the terrestrial environment	2020	115
Plastics in soil: Analytical methods and possible sources.	2018	104
Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth	2018	101
The distribution of microplastics in soil aggregate fractions in southwestern China	2018	98

The fourth most cited article was the first to conduct a pot experiment examining the effects of microplastics in soil on wheat growth, concluding that biodegradable mulch films have a more negative impact on wheat growth than traditional polyethylene mulch films[7]. The fifth most cited article studied the abundance distribution of microplastic aggregates in soil in southwestern China, showing that soil aggregates are associated with 72% of soil plastics[63].

Keyword Co-occurrence Analysis

Keywords are terms selected from the article that convey the main themes of the entire content and represent

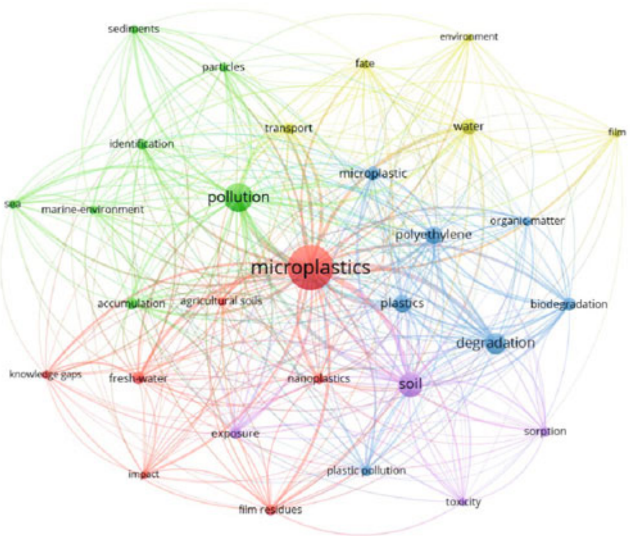

Figure 6. Keyword Co-Occurrence Analysis Network

the core of a paper. By analyzing the co-occurrence of keywords, one can grasp the research hotspots within a scientific field.

Using VOSviewer software, data from 325 articles were imported to create a keyword co-occurrence network map, as shown in Fig. 6. The visualization focused on the 30 main keywords that appeared more than 15 times. The results, as shown in Fig. 6, indicate that in papers published between 2013 and 2023, "Microplastics", "Pollution", and "Soil" were the most frequently occurring keywords. All the keywords in the visualization are grouped into five different clusters.

The red cluster includes keywords such as Microplastics (MPs), Agricultural soils, Film residues, Nanoplastics (NPs), and Impact. The commonly used plastics in agricultural films are predominantly polyethylene (PE), with some use of polyvinyl chloride (PVC) and ethylene-vinyl acetate (EVA). In recent years, various types of polyethylene, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE), have also been utilized. Biodegradable films have also become widely used. Research using Fourier Transform Infrared Spectroscopy has shown that the composition of microplastics found in soil is highly similar to that of agricultural films, indicating that plastic particles in the soil mainly originate from agricultural films[61]. These films, through processes of aging, weathering[64], or ultraviolet radiation, can transform into microplastics (1–5 mm) and nanoplastics (<1 μm)[65]. Studies have found that these plastics, once in the soil, can impact various aspects of the ecosystem, including the physicochemical properties of the soil, the health of plants and animals, and human health.

The green cluster includes representative keywords such as Accumulation, Identification, Marine-environment, Pollution, and Sediments. This cluster primarily focuses on the accumulation and distribution characteristics of microplastics from agricultural films. Long-term use of plastic films leads to the accumulation of plastic residues in the soil. For example, Ref.[66] found that after 32 years, plastic films account for 33%–56% of the total microplastics in soil at a depth of 100 cm. Ref.[67] reported that in soil covered for 30 years, the abundance of microplastics at a depth of 60 cm was 78.51±2.57 n/(100 g), indicating that long-term film coverage is a major source of soil microplastic pollution[68]. Additionally, the abundance of microplastics in soil increases with the duration of film coverage[69–71]. Ref.[71] found that microplastics are mainly concentrated in the 10–20 cm soil layer. Ref.[72] observed a significantly higher contribution of microplastics in the 10–25 cm soil layer, suggesting that microplastics are more likely to be distributed in deeper soil layers. The accumulation of microplastics in farmland soil is significantly related to factors such as soil restoration methods, human agricultural activities[73, 74], climate[75, 76], and soil type characteristics[77, 78].

The blue cluster includes keywords such as Biodegradation, Degradation, Organic-matter, Plastic Pollution, and Polyethylene. Agricultural films are difficult to degrade under natural conditions, resulting in a significant amount of residual film fragments in the soil. The degradation of biodegradable films is influenced by various factors, including soil conditions[28] and climate[79]. Additionally, biodegradable films may produce a large amount of microplastics in a short period, leading to significant uncertainties regarding their potential impact on soil environments[20]. The scalability of biodegradable films is also limited by cost, and their acceptance among farmers remains low[80], thereby affecting the soil carbon and nitrogen cycling system[81]. Ref.[81] demonstrated that biodegradable films might influence soil greenhouse gas emissions. They can also have toxic effects on soil plant health[82, 83], which in turn impacts food safety and increases human health risks[28]. Ref.[45] used the quadrant method to quantify plastics in field soils, finding that repeated application of biodegradable cover materials does not lead to microplastic accumulation in the fields, though their degradation time needs to be longer than one year. Ref.[84] proposed an innovative biodegradable film made from soybean protein isolate (SPI)/oxidized sucrose (OS)/lignin, which improved molecular interactions and tensile strength. While the goal of biodegradable films is to reduce environmental pollution caused by plastics, whether biodegradable plastics can replace traditional films remains to be debated[85].

In the yellow cluster, keywords such as “Transport”, “Water”, “Film”, and “Environment” indicate that researchers are focusing on the potential ecological risks posed by microplastics generated from agricultural films, particularly in relation to various transport mechanisms in the environment. Researchers have found that microplastics can be transported to deeper soil layers or groundwater with increased irrigation frequency, and the disruption of soil structure caused by irrigation may lead to a higher risk of microplastic leaching. Therefore, physically-based models specifically characterizing the transport of microplastics in soil driven by irrigation will be a key focus for future research[86]. Factors like irrigation water and surface runoff[87], natural wind[88, 89], and precipitation can all contribute to soil erosion[90], which may result in the migration of plastic particles from farmland to aquatic ecosystems[2].

The purple cluster includes keywords such as Exposure, Soil, Sorption, and Toxicity. Microplastics in soil can adsorb inorganic and organic pollutants or microorganisms on their surface through mechanisms such as electrostatic interactions, pore filling, van der Waals forces, hydrogen bonding, and π-π interactions[91]. Microplastics can act as carriers for common pesticides such as mancozeb and bifenthrin, thereby extending the persistence of these pesticides[92]. The shape and properties of microplastics can change during aging[93], leading to differences in how various microplastics affect the degradation of different pesticides[94], which in turn affects adsorption behavior. Microplastics are present in food and air samples consumed by humans, and harmful effects mainly occur through potential toxicity mechanisms. Ref.[95] found that microplastics can also serve as carriers for various antibiotics and heavy metals, which are adsorbed onto microplastics and spread in the environment. Ultimately, these substances can enter the human body through inhalation, ingestion, or skin contact, posing indirect risks to human health[96].

MIGRATION OF AGRICULTURAL FILM MICROPLASTICS IN SOIL

Biological Processes

Biological disturbance and plant root absorption[97], as well as microbial activity, are key biological processes influencing the migration of microplastics in soil. In terrestrial exposure assessments, biological disturbance is often not adequately considered as a migration mechanism. Research has shown that microplastics can migrate through soil due to animal movements and behaviors such as feeding. Studies have found that small soil animals can act as carriers of microplastics in the soil. After ingestion, microplastics are transported from the surface soil to deeper layers through feces, burrowing, excretion, and attachment to the animal’s body[98, 99]. Most studies have found that earthworm movements in the soil also facilitate the transport of a larger number of smaller microplastic particles to deeper soil layers[100]. It is hypothesized that feeding and excretion activities of soil animals serve as a non-local transport mechanism and are considered an important driving force for the vertical distribution of nanoplastics in cave ecosystems. Earthworms move microplastics from the soil surface to their burrows in a size-selective manner, reaching depths of up to 18 cm[101]. Studies also show that microplastic particles enter the soil through the actions of soil animals, with the smallest particles moving the most proportionally[98].

In addition to earthworms, other soil organisms, such as termites[102], nematodes, mites, springtails, amoebae, and more microarthropods, can also move and distribute microplastic particles[103]. In the soil, the activity of springtails and mites can promote the movement of microplastic particles along the soil profile to deeper layers, with mites playing a more significant role in facilitating microplastic migration[104]. Similarly, burrowing mammals such as voles and moles may accelerate the diffusion of microplastic particles in the soil through similar biological disturbance mechanisms[105]. Compared to the natural migration rate of microplastics under environmental conditions, the migration rate under the activities of voles and moles may increase several times due to their burrowing and carrying activities, which break up the original soil structure and thus reduce the resistance to microplastic migration. Biological disturbance is also influenced by external environmental factors[106].

Earthworms are not the only organisms capable of creating biological pores in the soil; plant roots can also form such pores and influence the migration of microplastics in the soil[105, 107]. The root structure and growth characteristics of different crops have varying effects on the migration of microplastics. Some studies have shown that corn roots may promote the upward movement of microplastics in the middle soil layers, while the number of microplastics is significantly positively correlated with ryegrass roots, indicating that the role of different crop roots in microplastic migration differs[108]. Plant roots not only affect the depth of microplastic migration but also alter their distribution patterns[109]. It has been found that the rhizosphere may form a zone of high microplastic concentration, while other areas exhibit lower concentrations. This uneven distribution may affect the structure and function of soil microbial communities[110].

Soil microbial communities alter the surface characteristics of microplastics through degradation processes, which in turn affect their movement in the soil. They can form biofilms on the surface of microplastics, changing their surface charge and hydrophilicity[111, 112], making them more mobile within soil pores[113]. Microbial activity can also promote the formation of soil aggregates, increasing soil porosity and providing more pathways for microplastic movement. Studies have found that some microorganisms can secrete extracellular polymeric substances (EPS), which bind with microplastic particles and cause them to remain in the soil[114]. The impact of different microbial communities on microplastic movement varies. Specific microbial communities may either accelerate or inhibit microplastic movement, depending on the type of microorganism, metabolic activity, and the interaction mechanisms with microplastics[115] (Fig. 7).

Abiotic Processes

The migration of plastic film-derived microplastics in soil is influenced not only by the physical and chemical properties of the microplastics themselves, such as particle size[116], but also by hydrodynamic transport, wind erosion[117], adsorption of organic pollutants, UV radiation[4], climate temperature[118], mechanical wear, agricultural practices[95, 119], and changes in the soil structure or properties[95]. In hydrodynamic transport, rainwater with a higher concentration of microplastics can cause some of the microplastics to be deposited into the soil under the influence of gravity[120]. Due to its scouring effect, microplastics may also be transported to areas with lower concentrations[121]. Hydrodynamic transport is clearly an important mechanism driving microplastic migration[122]. During this process, irrigation water can also facilitate the movement of microplastics in soil, and studies have shown that surface irrigation contributes more to soil microplastics than sprinkler or drip irrigation[119]. In the agro-pastoral ecotone of northern China, wind erosion events during the dry and windy spring season can lead to the accumulation of microplastics, such as plastic film residues, in downwind grasslands[123]. It has been found that smaller microplastic particles are more easily transported by wind during wind erosion, while larger microplastic particles decrease in quantity as the transport distance increases. Microplastics with relatively low density are transported horizontally by wind or precipitation[6, 88], whereas microplastics with relatively high density undergo vertical migration in the soil[123–125].

The adsorption of organic pollutants is an important factor influencing the migration of plastic film-derived microplastics in soil. After microplastics adsorb organic pollutants, their surface properties change, such as sur-

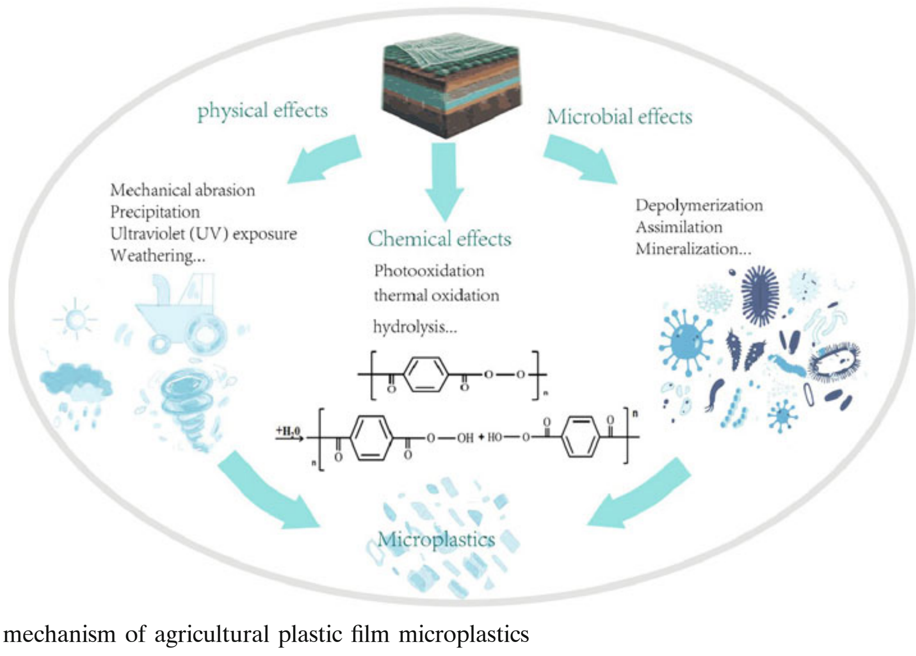

Figure 7. Formation mechanism of agricultural plastic film microplastics

face charge and hydrophilicity, which in turn affect the interactions between microplastics and soil particles, altering their migration paths in the soil[126]. In particular, the adsorption of certain organic pollutants can enhance the hydrophobicity of microplastics, making them more mobile within soil pores[127]. The surface chemical groups of microplastics can also affect their migration; for example, neonicotinoid compounds can promote the transport of polyethylene and polypropylene microplastics[91]. Ref.[4] found that as ultraviolet (UV) radiation exposure time increased, the proportion of smaller microplastics increased, especially for biodegradable plastic films. UV radiation also makes the surface of microplastics rougher, accelerating their aging process and thus influencing their interaction with soil particles[128]. Studies have shown that rising temperatures accelerate the thermal degradation of microplastics, changing their physicochemical properties[129], and also reduce the proportion of soil water-stable aggregates, leading to a decline in soil quality, which in turn affects the migration of microplastics[130]. In agricultural activities such as tilling and plowing, machinery causes strong physical disturbances to the soil. This disturbance destroys the original soil structure, leading to the reorganization of soil particles and the formation of new pores and channels. Microplastic particles can move more freely through these newly formed pores, thus accelerating their migration rate in the soil[131]. Different soil types also have varying impacts on migration. Sandy soils have the highest microplastic migration ability, at 30.51%[95]. In agricultural soils, the contributions of silty and sandy particles are significantly correlated with microplastic abundance, whereas clay particles show no significant correlation with microplastic abundance[119].

IMPACT OF AGRICULTURAL FILM MICROPLASTICS ON SOIL ECOSYSTEMS

Plants

The impact of microplastics from agricultural films on plants is not only due to their effects on soil properties, such as the carbon-to-nitrogen ratio[132, 133], the size distribution of water-stable soil aggregates, and soil permeability[134], which in turn disrupts the plant's ability to access water and nutrients provided by the soil. Research has also found that microplastics can affect plant growth through nitrogen metabolism and photosynthesis[82]. Moreover, under different soil pH levels, the negative impact of film residues on rice growth is stronger in acidic soil conditions[135], including different types of agricultural films[7]. The effects on plant growth also vary depending on the type of agricultural film used. For instance, studies have shown that compared to polyethylene films, biodegradable films have a stronger negative impact on plant growth[136, 83]. However, whether these impacts are directly due to microplastics causing cellular expansion in plants or indirectly due to factors like nutrient deficiency and soil acidification still requires further investigation[28] (Fig. 8).

The presence of microplastics from agricultural films does not always have negative effects on plants. Some researchers have found that microplastics can have a positive impact on root growth, potentially leading to an increase in root biomass. This expansion of the root system enhances the plant's ability to meet its water and nutrient needs, thereby promoting overall plant growth. Regarding the toxic effects of microplastics on plants, studies have shown that the toxicity is not solely dependent on the accumulation of microplastics in the soil. Instead, the different functional groups on the surface

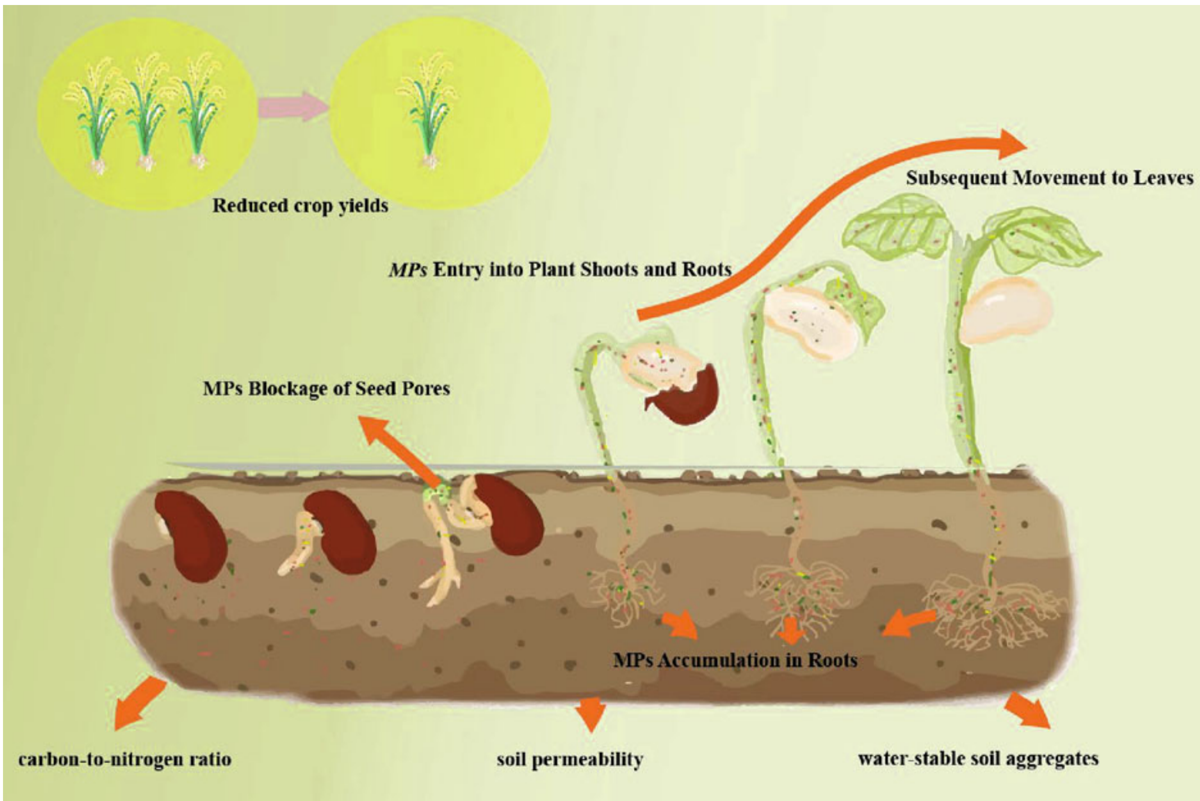

Figure 8. Diagram of the mechanisms of mulching film microplastics on plants

of microplastics can cause varying degrees of toxicity to plants[97] (Fig. 8).

Animals

As a key soil-dwelling animal, earthworms have been found to be negatively affected by the presence of microplastics derived from plastic films in soil, impacting their growth, behavior, reproduction, gut microbiota, and physiological responses[137]. Studies by[138] and others have shown that polyethylene microplastics can cause disruptions to intestinal barrier function, gut microbiota imbalance[139], and varying levels of DNA damage in the coelom cells of earthworms, depending on the size and concentration of the microplastics[140, 141]. These microplastics can also lead to metabolic disorders and, in some cases, affect the reproductive systems of animals, resulting in hormonal imbalances, reduced sperm counts, and other harmful effects[142]. Furthermore, the presence of microplastics can suppress serum levels of follicle-stimulating hormone and luteinizing hormone, impairing reproduction in soil animals[143], and may even lead to transgenerational effects[144] (Fig. 9).

Soil microplastics can also impact human health through their effects on crops and farmland organisms, with potential transmission through the food chain. Studies have shown that microplastics can be present in the human gastrointestinal tract, causing gut microbiota imbalances[145], impaired gut barrier function, and intestinal inflammation, and may enter the bloodstream through the digestive mucosa[146]. They have also been confirmed to enter human kidneys and liver, affecting cell morphology, metabolism, and proliferation[147], and can interfere with the immune system, potentially increasing the incidence of immune-related diseases[148, 149]. Multiple studies suggest that the presence of microplastics may be associated with metabolic disorders, neurological damage, and an increased risk of cancer[150]. Further research is urgently needed to accurately assess the specific impacts and mechanisms of microplastics on human health.

Microorganisms

Microplastics can affect soil microbial metabolic functions[13, 150], microbial activity[151], and microbial diversity[11, 152]. Microplastics provide new habitats for microorganisms, forming unique microbial biofilms that are significantly different from the surrounding microbial communities. For example, studies have shown that microplastics can harbor different microbial communities, which may aid in the dispersal of microbial species between different habitats[152, 153]. This phenomenon is of particular concern because the biofilms on microplastics could serve as carriers for pathogenic microorganisms, altering the dynamics of microbial communities and even promoting the spread of antibiotic-resistant genes[154, 155]. Additionally, the presence of microplastics is linked to changes in microbial metabolic processes, especially in organic matter degradation and nutrient cycling, which are crucial for ecosystem health[156].

Some studies have found that microplastics strongly inhibit the recovery of bacterial community richness[5], while other researchers have suggested that low concentrations of polyethylene microplastics may promote bacterial community richness[59]. This indicates that the effect on bacterial community richness varies depending on the concentration of microplastics. The exposure time and residual concentration of microplastics in the soil are important factors influencing microbial communities (Fig. 10).

Current research on the effects of microplastics on soil microorganisms primarily focuses on bacterial and fungal communities. Most studies suggest that the abundance of Actinobacteria, Bacteroidetes, and Proteobacteria is signi-

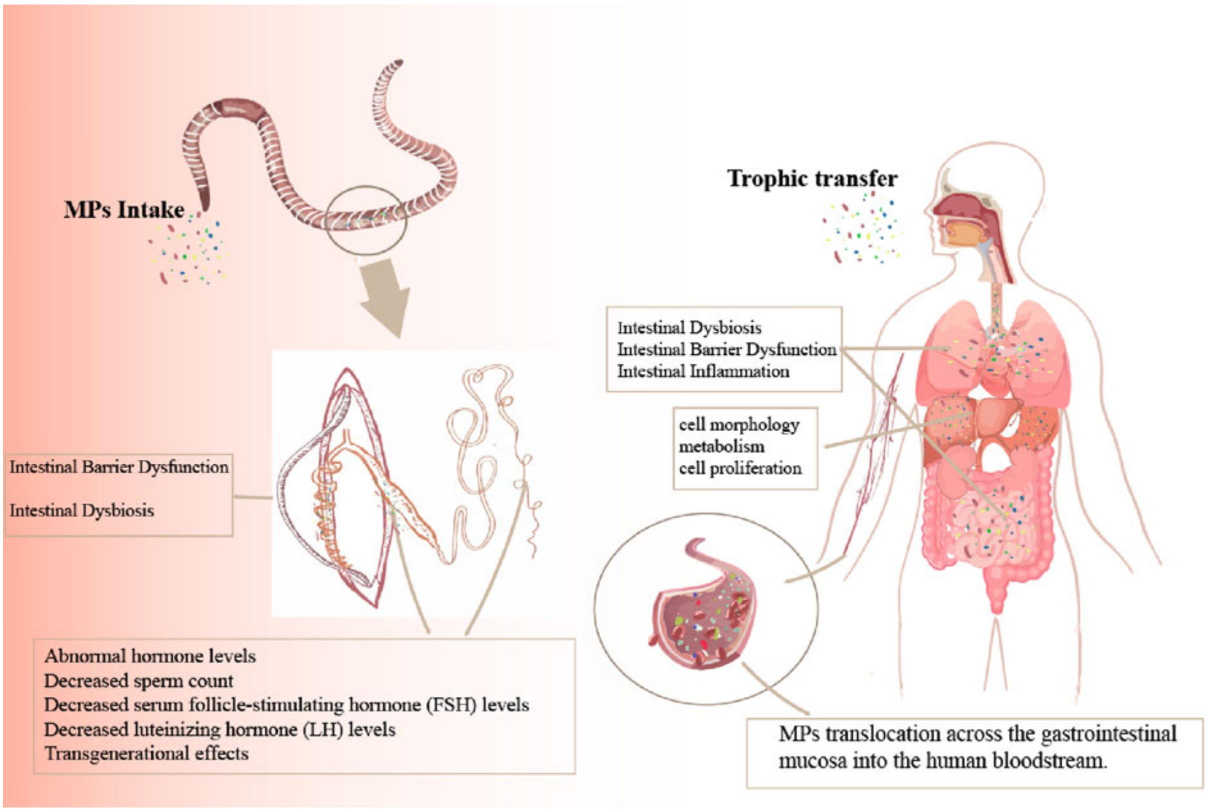

Figure 9. Diagram of the mechanisms of mulching film microplastics on soil fauna and human health

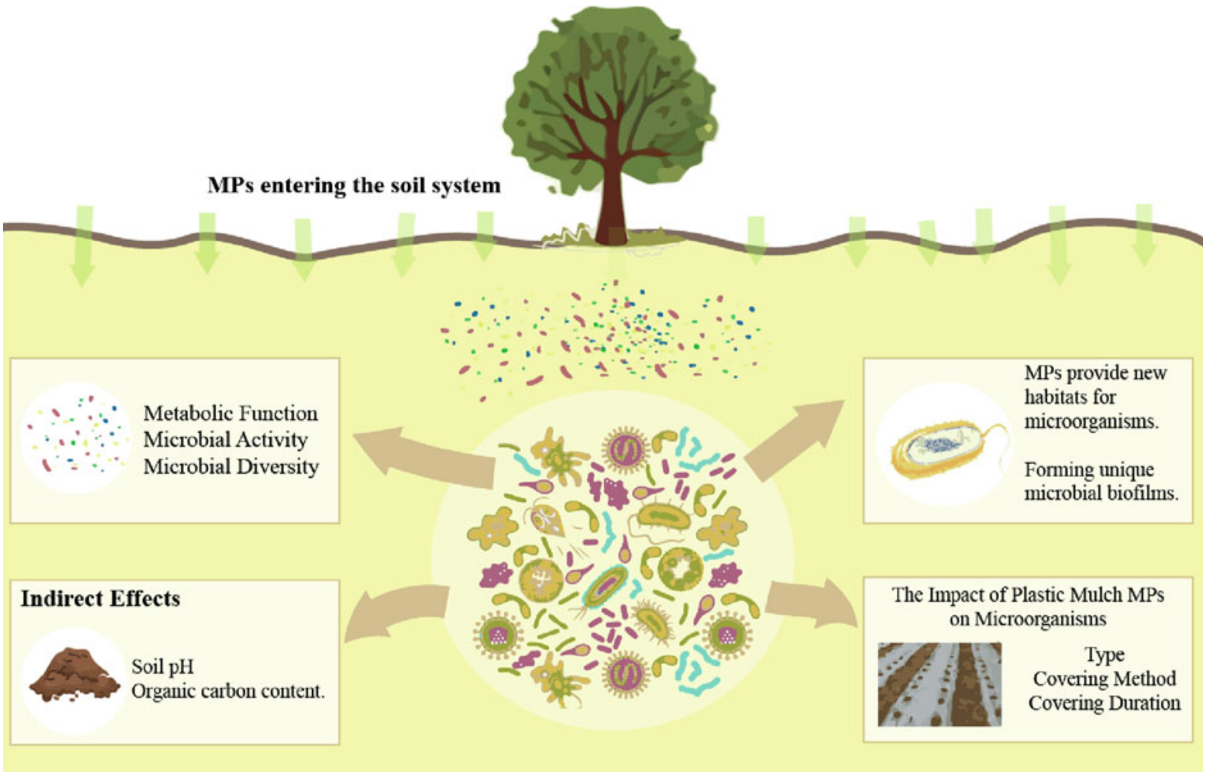

Figure 10. Diagram of the mechanisms of interactions between mulching film microplastics and soil microorganisms

ficantly higher than that of other microbial groups[13, 14]. There are also interactions between microplastics and soil microorganisms, with some microorganisms potentially playing a role in the degradation of microplastics in the soil[13]. The impact of microplastics derived from plastic films on soil microorganisms also depends on factors such as the type of plastic film[157], the coverage method[11], and the number of years of coverage[158]. Microplastics may also indirectly affect microbial communities by altering the physical and chemical properties of the soil (e.g., pH and organic carbon content). In addition, the interactions between microplastics and microorganisms may be influenced by environmental factors such as salinity and nutrient availability, further complicating the understanding of these relationships[159, 160].

COMBINED EFFECTS OF FILM-DERIVED MICROPLASTICS AND PESTICIDES

Pesticides play a crucial role in agriculture, being used to control pests and weeds. However, during their application, these chemicals can seep into the soil and gradually accumulate. At the same time, the widespread use of plastic mulch films and pesticides in farmland leads to the coexistence of microplastics (MPs) and pesticide residues in the soil over time. This combined effect may exacerbate the overall soil pollution problem.

Research on the interaction between film-derived microplastics and pesticides primarily focuses on aspects such as pesticide adsorption, desorption, and degradation on agricultural polyethylene microplastics[161]. Some studies have compared the adsorption capabilities of five common agricultural pesticides—carbendazim, cyhalofop-butyl, diflufenican, malathion, and benzimidazole—finding that their adsorption to microplastics is mainly based on hydrophobic interactions, along with electrostatic and valence bond interactions[92]. Other studies have observed that pesticides exhibit stronger adsorption capacities on aged agricultural polyethylene microplastics compared to fresh polyethylene microplastics, and biodegradable film microplastics also show greater adsorption capacity than those derived from traditional films[162]. These findings highlight the crucial role of hydrophobic distribution in adsorption processes and contribute to risk assessments of pesticide and microplastic co-exposure (Fig. 11).

The degradation of soil plastics can be influenced by factors such as the interaction between pesticides and plastic mulch. For example, during the application of pesticides like prothioconazole, contact with plastic mulches in the soil may occur. Researchers have studied the impact of prothioconazole on the degradation of microplastics derived from conventional polyethylene film and biodegradable mulch film. Biodegradable microplastics have shown higher adsorption efficiency compared to traditional microplastics[161]. This characteristic allows them to degrade faster than polyethylene plastic films. The use of pesticides has been proven to accelerate the degradation of microplastics derived from plastic mulch films. Due to the interaction mechanisms between microplastics and pesticides, the presence of microplastics also affects the degradation of pesticides. Ref.[94] studied the impact of two different pesticides on the degradation of mulch film microplastics in soil, and the results showed that both new and traditional mulch film microplastics could accelerate the degradation of these pesticides. In contrast, aged traditional mulch microplastics and biodegradable mulch microplastics inhibited pesticide degradation. Additionally, an increase in microplastic concentration further intensified this effect, leading to more significant changes in pesticide degradation rates.

The combined effects of microplastics derived from plastic mulch and pesticides on terrestrial organisms is another important issue that requires attention. Research has found that the co-exposure of microplastics from

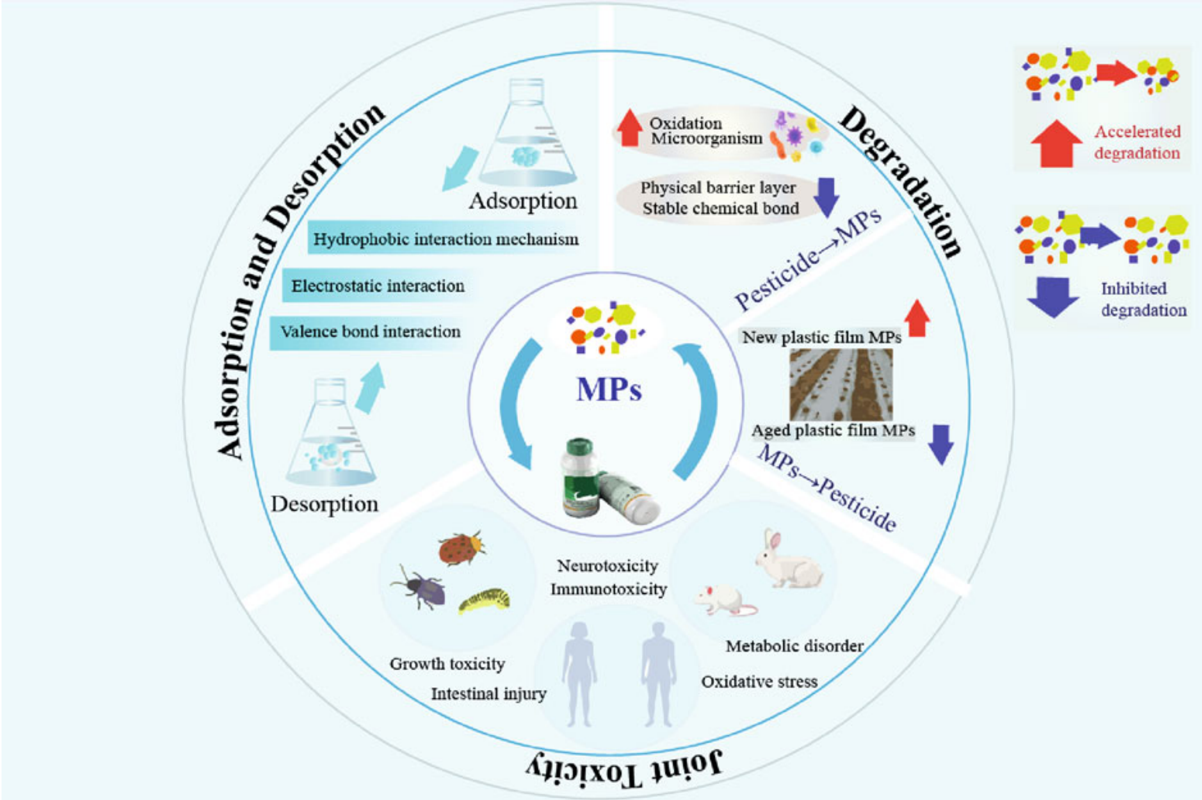

Figure 11. Diagram of the mechanisms of interactions between microplastics and pesticides, and their combined toxicological effects

mulch films and pesticides in soil environments may exacerbate oxidative stress in earthworms and lead to changes in their gene expression patterns[163].

In addition to pesticides, other soil contaminants such as heavy metals may also interact intricately with microplastics, impacting their behavior, mobility, and bioavailability in the environment. These pollutants can adhere to or bind with microplastics, potentially altering their persistence in soil and their toxicity to organisms. The combined effects of heavy metals and microplastics could further exacerbate risks to soil ecosystem health. Future research could focus on the ecological toxicity arising from multiple contaminants, aiming to deepen the understanding of microplastic behavior and ecological impact within complex environmental settings.

CONCLUSIONS AND FUTURE DIRECTIONS

This study employs VOSviewer and Citespace software to conduct a visual analysis of the research on microplastic pollution from agricultural plastic films over the past decade. It systematically reviews the development trends in this field, and applies Lotka's Law from scientometrics to analyze the core authors in this area. The study also examines core journals, leading authors, high-productivity national institutions, co-citation networks, author clusters, and keyword clusters.

The analysis reveals that the collaboration groups among authors have become relatively stable. A core journal in this field has been established, identified as Science of The Total Environment. Chinese scholars have published the most papers in this area, and their work is highly recognized, as indicated by the average citations per paper. Keyword co-occurrence and cluster analyses suggest that several relatively stable clusters have formed, including the impact of microplastics from agricultural films on ecosystems, factors influencing the migration of microplastics in soil, the effects of microplastics derived from plastic films on flora and fauna within ecosystems, and the combined effects of microplastics with agricultural pesticides on adsorption and degradation. Author cluster analysis indicates that an authoritative group of authors has emerged in this field, significantly influencing its development.

Despite the growing body of research on microplastics derived from agricultural mulch films, current studies still face several notable limitations. Methodological inconsistencies remain a major challenge, particularly the lack of standardized protocols for sampling, extraction, and identification of soil microplastics. Diverse analytical techniques, along with differences in the types, sizes, and polymer compositions of microplastics studied, result in data variability and hinder cross-comparison of findings. Additionally, regional factors such as soil type, climate, and land use patterns contribute to site-specific results, complicating generalization across studies. For instance, microplastic abundance may differ significantly between agricultural regions like the Tibetan Plateau and southern China due to differences in human activity and climatic conditions such as humidity and rainfall, which influence degradation rates.

Furthermore, the long-term ecological impacts of soil microplastics remain inconclusive. While some studies report notable effects on soil organisms and plant growth, others find minimal impact—possibly due to variations in exposure duration and concentrations. The potential health risks of microplastics through food chains also require long-term ecotoxicological and epidemiological studies to fully assess their chronic toxicity and bioaccumulation effects.

Some new types of biodegradable films are expected to replace traditional plastic films to address the issue of film pollution. However, the ecological risks associated with biodegradable films, particularly regarding the generation and ultimate fate of microplastics, remain highly uncertain. Additionally, factors such as cost, farmers' acceptance, and the performance of biodegradable films under different soil environments and climatic conditions are significant barriers to their widespread adoption and application in agriculture. To mitigate these issues, it is essential to intensify research on the environmental effects of new biodegradable films, with a particular focus on the generation and fate of microplastics. Through rigorous scientific experiments and sampling, more data can be obtained to comprehensively assess their environmental impact. Clear guidelines for the use, recycling, and disposal of new biodegradable films should be established to minimize their potential environmental risks and promote their sustainable development and application. Additionally, more in-depth studies should be conducted on the migration and transformation patterns of microplastics in soil environments, as well as their impact on soil ecosystems, and the remediation of microplastic pollution.

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Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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