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REVIEW

Current Situation and Ecological Effects of Microplastic Pollution in Soil

Minggu Zhang[1] · Miaomiao Tan[1] · Rong Ji[2] · Ronghui Ma[3] · Chengliang Li[1]

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Abstract
Microplastics have received more and more attention worldwide as an emerging persistent pollutant. Soil microplastic pollution can cause serious environmental problems and potentially endanger the soil ecosystems and human health. Currently, most available studies of microplastics have been performed in aquatic environments. However, soil environments have been less studied, and our understanding of microplastic pollution in soil is still lacking. Therefore, based on the existing knowledge, this review firstly focuses on the current situation of microplastic pollution in soil, basically including sources, distribution characteristics, degradation, and migration. Furthermore, analytical methods are briefly discussed, and ecological effects of microplastics in soil are summarized. Soil is a reservoir of microplastics. Microplastics have a wide distribution and high abundance in environmental media, and their distribution in soil exhibits spatial heterogeneity. Microplastics affect soil physicochemical properties, soil microorganisms, soil fauna, and plants through several mechanisms, leading to different ecological effects. Finally, future research directions of soil microplastic pollution are proposed to provide novel ideas for follow-up research.

Keywords Microplastics · Soil · Current situation · Ecological effects

Abbreviations

ARGs	Antibiotic resistance genes
PA	Polyamide
PBS	Polybutylene Succinate
PE	Polyethylene
PES	Polyester
PET	Polyethylene terephthalate
PHAs	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PHBV	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate)
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PSNP	Polystyrene nanoplastics
PU	Polyurethane
PVC	Polyvinyl chloride
SBR	Synthetic Blend Rubber
TRWP	Tyre and road wear particulates
UV	Ultraviolet

✉ Chengliang Li
chengliang_li11@163.com

Minggu Zhang
zhangminggu0@163.com

Miaomiao Tan
18763825376@163.com

Rong Ji
ji@nju.edu.cn

Ronghui Ma
maronghui518@163.com

[1] College of Resources and Environment, Shandong Agricultural University, Taian, China

[2] School of Environment, Nanjing University, Nanjing, China

[3] Agricultural Technology Promotion Center of Shandong Province, Jinan, China

Introduction

Plastics are durable, multi-functional, and cost-efficient polymer materials, which mainly include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyester (PES), polylactic acid (PLA), and polyamide (PA) (Duis and Coors 2016). Plastics are widely used in all industries, and their waste generation has increased over time on global scale. Lau et al. (2020) estimated that 710 million metric tons of plastic waste cumulatively entered aquatic and terrestrial ecosystems till 2040, if governments took immediate environmental actions.

The plastics in the environment are usually cracked into plastic fragments or particles by physical, chemical, and biological processes (Barnes et al. 2009). The concept of microplastic was firstly coined in 2004 (Thompson et al. 2004). Microplastics are typically considered plastic fragments or particles with a diameter of below 5 mm with ranges that vary between studies (Law and Thompson 2014). Microplastics are characterized with small particle size, wide distribution, high abundance, and stable chemical properties (Bergmann et al. 2019; Li et al. 2020a; Padervand et al. 2020; Revell et al. 2021). They can easily adsorb various types and enrichment of toxic chemicals or microorganisms on the surface and be ingested by soil-dwelling biota, thereby interfering with environmental behavior of soil organisms (Law and Thompson 2014; Rillig 2012).

Our cognition of microplastics in soil is still fragmented (Fig. 1). Hence, based on recent studies, this review comprehensively summarizes the current situation and ecological effects of microplastic pollution in soil.

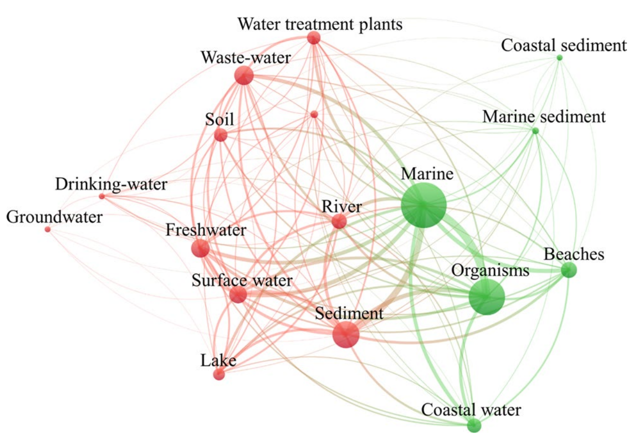

Fig. 1 Co-occurrence network analysis of keywords in microplastic publications. The VOSviewer software (version 1.6.15) was selected for co-occurrence network analysis. The retrieval strategy was "topic = (microplastic) or (microplastics)". The literature data were obtained from the Web of Science at the retrieval time of 4/05/2022. After removing the irrelevant keywords, 17 keywords related to natural environment were selected for bibliometrics. The size of a node is positively correlated with the occurrence frequency of the keywords. The thickness of a link is positively correlated with the correlation between the keywords

Current Situation of Microplastic Pollution in Soil

Sources of Microplastics in Soil

It is widely accepted that plastic film mulching, sewage sludge, compost, and irrigation are the main sources of microplastics in soil (Li et al. 2022b; Qadeer et al. 2021; Ragoobur et al. 2021; Yang et al. 2021a, 2022). Although a number of studies have quantified the composition of microplastics in soil, it is still not possible to accurately identify the proportion from different sources (Zhang et al. 2020).

The sources of microplastics in soil are diverse and extensive because of the different land use types (Rillig and Lehmann 2020). Most research on sources of soil microplastics has focused on agricultural soil to date. Rillig and Lehmann (2020) expected that agricultural soil contained the largest amount of microplastics compared with other terrestrial soil. Many studies indicated that sewage sludge (Hamidian et al. 2021; Weber et al. 2022), organic fertilizer (Weithmann et al. 2018), and plastic film mulching (Li et al. 2022b) were vehicles for the entry of microplastics into agricultural soil. Huang et al. (2020) found a highly significant linear correlation ($R^2 = 0.61$) between the consumption of plastic film mulching and the plastic residue in soil. Agricultural soil exhibited high microplastic abundance and most of the identified microplastics were PE films (Piehl et al. 2018; Wang et al. 2021a).

The wetland soil has more diverse sources of microplastics because of the exposition to various pollution sources. The common types of microplastics in wetlands are PE, PP, and PS (Kumar et al. 2021). Kumar et al. (2021) perceived that primary sources of microplastics in wetlands were dumped directly by industries, household activities, and treatment plants. Ouyang et al. (2022) found that fibers were the dominant form of microplastics particles in coastal wetlands, implying that sewage was a primary source of microplastics in coastal wetlands. In Qinzhou Bay, the major sources of microplastics in wetland soil are attributed to aquaculture (*e.g.,* woven bags, fish nets) (Li et al. 2018b).

Considering microplastic pollution in agricultural soil, that in roadside soil has been relatively neglected. The microplastic contamination of roadside soil due to traffic-related activities have been a severe issue. Tyre and road wear particulates (TRWP) are an important source of microplastics in roadside soil. The TRWP production contributes to more than half of the total microplastics produced in North European countries (Campanale et al. 2022), and most of TRWP (74%) are deposited on roadside soil (Sieber et al. 2020). Muller et al. (2022) determined that 155 to 1.16E + 04 mg kg^{-1} TRWP were detected in soil along a German motorway.

Altogether, there are multiple routes through which microplastics can enter soil. This may cause great pressure on the soil microplastic pollution and prevention. Preventing microplastics from entering the environment also become a major problem faced by all countries so far.

Distribution Characteristics of Microplastics in Soil

Wide Distribution and High Abundance

Microplastics have strong persistence in natural environments due to their durability, corrosion resistance, and anti-biodegradable properties (Xu et al. 2020). As a newly emerging type of environmental persistent complex pollutant, microplastics can be migrated over long distances and reach inaccessible places by external forces such as rivers, tides, and winds (Cozar et al. 2014; Wang et al. 2019c). Consequently, microplastics are ubiquitous from the land surface to the depths of the ocean, from city centers to polar glaciers, and from the equator to the north and south poles (Barnes et al. 2010; Eriksen et al. 2014; Kanhai et al. 2017; Peeken et al. 2018; Zhang et al. 2018b).

Compared with marine microplastic pollution, soil microplastic pollution has been largely overlooked, even when the soil holds higher volumes of microplastics (van Sebille et al. 2015). Horton et al. (2017) showed that the plastics released to the terrestrial environments annually were estimated at 4–23 times higher than that released to marine environments. It is estimated that 6.30E + 04–4.30E + 05 and 4.40E + 04–3.00E + 05 tons per year of microplastics are released into European and North American farmlands through sludge, respectively, which exceed the cumulative count of microplastics in the global ocean surface water (Nizzetto et al. 2016b; van Sebille et al. 2015). The average concentration of microplastics in agricultural soil covered by a plastic film for 30 years is as high as 83.6 kg hm^{-2} in China (Huang et al. 2020). Mo et al. (2021) estimated that 68 tons of microplastics had been annually released into soil from plastic gauze. In conclusion, microplastics in soil have a wide distribution and high abundance.

Presenting Spatial Heterogeneity

Nowadays, there is still a lack of knowledge about the occurrence and distribution of microplastics in soil. Table 1 shows the distribution and abundance of soil microplastics in parts of world and displays obvious spatial heterogeneity. Of microplastics in soil, PP, PE, and PET are common polymer compositions, and the abundance is below 5000 particles kg^{-1} in the great majority.

Currently, the studies of soil microplastic distribution in global scale are shown in Fig. 2, and most of them focus on China. Spatial distribution and abundance of microplastic in soil are uneven in China (Fig. 2 and Table 1). As shown in Table 1, agricultural soil possesses high microplastic abundance, and PP and PE are dominant. The possible reason for this result is the extensive use of mulch. Zhou et al. (2020a) demonstrated that the mulching field contained more than twice the non-mulching field on the coastal plain of Hangzhou Bay, which was averagely 571.2 particles kg^{-1} dry weight and 262.7 particles kg^{-1} soil with dry weight basis, respectively. Huang et al. (2020) investigated 384 soil samples collected from 19 provinces across China and reported that the abundance of microplastics in western China was higher than that in eastern China, possibly due to the higher use of mulching film.

Among soil microplastic research reported outside China, few of which focus on microplastic distribution (Büks and Kaupenjohann 2020). Rezaei et al. (2019) investigated the presence of low-density microplastics in soil and wind-eroded sediment of Fars Province, which was the first study on the transport of soil microplastics by wind erosion. They found that microplastic concentration ranged from 67 to 1133 particles kg^{-1}, and wind-eroded sediment was enriched with microplastics with a ratio of 2.83 to 7.63. In Amsterdam, peat soil has abundant microplastics, with a mean of 4825.31 ± 6513.85 particles kg^{-1} (Cohen et al. 2021). In Central Germany, Weber et al. (2022) investigated loads of 0.00 to 56.18 particles kg^{-1} dry weight for agricultural soil after 34 years without sewage sludge application.

However, existing investigation data as mentioned above lack comparability because of the diversification methods for microplastics in soil. The distribution and abundance of microplastics in soil are closely relative to the natural geographical characteristics, human activity intensity, population density, gross domestic product (GDP), and industrial production. However, there are scarce reports on the systemic distribution of microplastics in soil up to date, and further research should better focus on specific influencing factors of microplastics.

Size Effect on Microplastic Distribution

The abundance of microplastics with different particle sizes is various in soil environments. In general, the abundance of microplastics is negatively correlated with their sizes. Microplastics in small sizes have relatively high number abundance overall (Hu et al. 2022; Zhou et al. 2016). Liu et al. (2018) found the fraction below 1 mm had the largest proportion, which occurred 48.79% of the microplastics in shallow soil (0–3 cm) and 59.81% of the microplastics in deep soil (3–6 cm). Zhang and Liu (2018) suggested that the microplastics with 0.25–0.05 mm particle size accounted for the highest proportion in the topsoil of each plot. This finding matches with the result that small and medium-sized microplastics dominate considerably in marine environments

Table 1 Distribution characteristics of soil microplastics in several parts of the world

Location	Soil type	Abundance (particles kg^{-1} dry weight)	Size range	Component	Reference
Turkey (Adana/Karataş)	Agricultural soil	16.5 ± 2.4	55 μm-5 mm	–	Gundogdu et al. (2022)
Korea (Yeoju)	Traffic soil	1108	< 5 mm	SBR, PP, PE	Choi et al. (2020)
Korea (Yeoju)	Agricultural soil	664	< 5 mm	SBR, PP, PE	Choi et al. (2020)
Korea (Yeoju)	Residential soil	500	< 5 mm	SBR, PP, PE	Choi et al. (2020)
Korea (Yeoju)	Forest soil	160	< 5 mm	SBR, PP, PE	Choi et al. (2020)
Pakistan (Lahore)	Agricultural soil	3712 ± 2156	50 μm-5 mm	–	Rafique et al. (2020)
Pakistan (Lahore)	Roadside soil	3915 ± 1499	50 μm-5 mm	–	Rafique et al. (2020)
India (Karnataka)	Riverside soil	84.45	0.3–5 mm	PE, PET, PP	Amrutha and Warrier (2020)
Spain (Eastern)	Agricultural soil	2030	50 μm-5 mm	–	van den Berg et al. (2020)
Australia (Sydney)	Plastic industrial area soil	7764.7	< 1 mm	PVC, PE, PS	Fuller and Gautam (2016)
Chile	Agricultural soil	1100–3500	< 1 mm	–	Corradini et al. (2019)
Germany (Lahn River)	floodplain soil	1.88 ± 1.49	2–5 mm	PE, PP, PA	Weber and Opp (2020)
Germany (Southeast)	Agricultural soil	0.34 ± 0.36	< 5 mm	PE, PP, PS	Piehl et al. (2018)
Germany (Central)	Agricultural soil	0.00–56.18	< 5 mm	–	Weber et al. (2022)
Germany (Northern)	Agricultural soil	0.00–217.8	1 mm-5 mm	PE, PP	Harms et al. (2021)
Netherlands (Amsterdam)	Peat soil	4825.31 ± 6513.85	< 5 mm	PE, PAC, PA	Cohen et al. (2021)
Mexico (Southeast area)	Agricultural soil	870 ± 1900	< 5 mm	PE, PS	Lwanga et al. (2017b)
Iran (Fars province)	Agricultural soil	205 ± 168	40 μm-740 μm	–	Rezaei et al. (2019)
Switzerland	Floodplain soil	593	< 2 mm	PE, PS, PVC	Scheurer and Bigalke (2018)
Singapore	Coastal mangrove sediment	36.8	< 5 mm	–	Nor and Obbard (2014)
China (Guizhou Plateau)	Agricultural soil	3000–8640	5 μm-5 mm	–	Zhang et al. (2022a)
China (Xinjiang)	Plastic film mulched soil	2.13E + 04 ± 7200	10 μm-5 mm	PP, PVC, PE	Jia et al. (2022)
China (Qinghai)	Agricultural soil	240–3660	0.45 μm-5 mm	–	Lang et al. (2022)
China (Guangxi)	Coastal mangrove sediment	875.3	50 μm-5 mm	PP, PS	Zhou et al. (2020b)
China (Fujian)	Coastal mangrove sediment	198.4	50 μm-5 mm	PP, PS	Zhou et al. (2020b)
China (Hainan)	Coastal mangrove sediment	146.0	50 μm-5 mm	PP, PS	Zhou et al. (2020b)
China (Zhejiang)	Coastal mangrove sediment	116.7	50 μm-5 mm	PP, PS	Zhou et al. (2020b)
China (Guangdong)	Coastal mangrove sediment	98.7	50 μm-5 mm	PP, PS	Zhou et al. (2020b)
China (Shihezi)	Green-belt soil	287–3227	20 μm-5 mm	PS, PE	Liu et al. (2022b)
China (Tibet)	Plateau soil	47.21	2 mm-5 mm	PVC, PP, PE	Yang et al. (2022)
China (Yangtze plain)	Riparian soil	3877 ± 2356	0.45 μm-5 mm	PE, PP	Zhou et al. (2021b)
China (Inner Mongolia)	Agricultural soil	2526–6070	0.45 μm-5 mm	–	Wang et al. (2020)
China (Yangtze plain)	Agricultural soil	4.94–252.7	< 5 mm	PP	Cao et al. (2021)
China (Jiangxi)	Agricultural soil	16.4 ± 2.7	< 5 mm	PP, PES, PE	Yang et al. (2021b)
China (Shanxi)	Agricultural soil	1430–3410	0.45 μm-5 mm	PS, PE, PP	Ding et al. (2020b)
China (southwest area)	Agricultural soil	40–100	50 μm-10 mm	PE, PP	Zhang and Liu (2018)
China (Shanghai suburbs)	Agricultural soil	78.00 ± 12.91	20 μm-5 mm	PP, PE	Liu et al. (2018)
China (Yunnan)	Agricultural soil	1.97E + 04	50 μm-10 mm	PP, PE	Zhang and Liu (2018)
China (Northwest area)	Agricultural soil	550–1.19E + 04	3 μm-5 mm	–	Cheng et al. (2020)
China (Shandong)	Agricultural soil	1444 ± 986	< 5 mm	PP, PE	Yu et al. (2021b)
China (Wuhan)	Agricultural soil	986	20 μm-5 mm	PP, PA, PS	Chen et al. (2020b)
China (Yunnan)	Wetland soil	1.50E + 04	50 μm-10 mm	PP, PE	Zhang and Liu (2018)
China (Yunnan)	Gully soil	2.41E + 04	50 μm-10 mm	PP, PE	Zhang and Liu (2018)
China (Hebei)	Coastal tidal flat soil	158.5	< 5 mm	PE, PP, PVC	Zhou et al. (2016)
China (Shandong)	Coastal tidal flat soil	1.3–14.7125	< 5 mm	PE, PP, PS	Zhou et al. (2018)
China (Shanghai)	Rice-fish co-culture soil	10.3 ± 2.2	20 μm-5 mm	–	Lv et al. (2019)
China (Daliao River)	Loam soil	60–980	5 μm-5 mm	PP, PE	Han et al. (2020)
China (Shanghai suburbs)	Solonchak	256.67 ± 62.20	< 5 mm	PP, PE	Liu et al. (2018)

Table 1 (continued)

Location	Soil type	Abundance (particles kg^{-1} dry weight)	Size range	Component	Reference
China (Shanghai suburbs)	Paddy soil	190 ± 31.22	< 5 mm	PP, PE	Liu et al. (2018)
China (Shanghai suburbs)	Loam soil	155 ± 95.17	< 5 mm	PP, PE	Liu et al. (2018)
China (Shanghai suburbs)	Fluvo-aquic soil	136.67 ± 41.67	< 5 mm	PP, PE	Liu et al. (2018)
China (Mu Us Sand Land)	Sandy soil	2696.5	< 5 mm	PP, PE, PS	Ding et al. (2021b)
China (Hangzhou Bay)	Plastic film mulched soil	571.2	60 µm-5 mm	PE, PP, PS	Zhou et al. (2020a)
China (Hangzhou Bay)	Non-mulched soil	262.7	60 µm-5 mm	PE, PP, PS	Zhou et al. (2020a)
China (Xinjiang)	Plastic film mulched soil	80.3–1075.6	7 µm-5 mm	PE	Huang et al. (2020)
China (Northwest)	Plastic film mulched soil	388.92	< 2 mm	PE	Meng et al. (2020)
China (Shenyang)	Plastic film mulched soil	7183–1.06E + 04	< 5 mm	–	Li et al. (2022b)

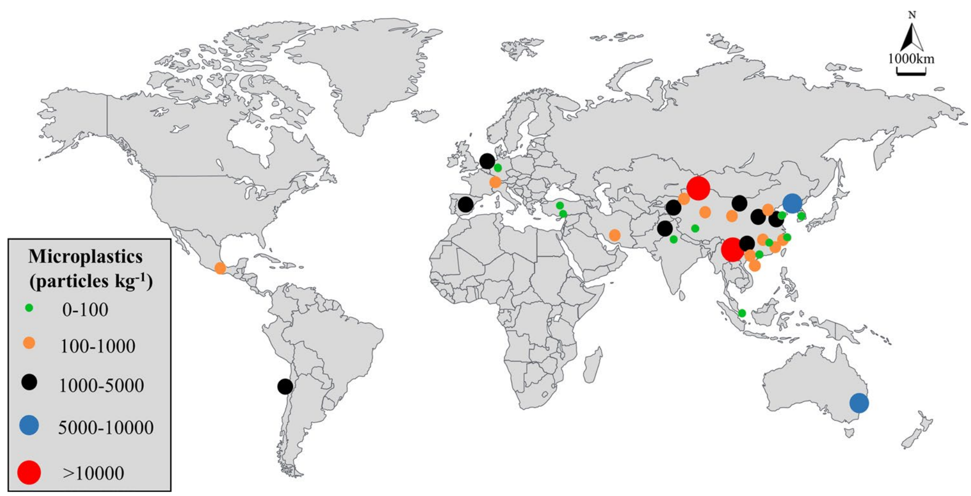

Fig. 2 Global view of microplastics in soil (Based on Table 1)

(Jayasiri et al. 2013; Martins and Sobral 2011). Currently, the microplastics below 1 µm size have attracted the attention of scholars, which are easier to penetrate the cell membrane and enter biological tissues and cells, as a result, more attention is demanded in further studies (Lusher et al. 2013; von Moos et al. 2012).

Land Use Patterns Affect the Distribution Characteristics

Different land use patterns are influenced by human activities of varying intensity, resulting in distinct microplastic sources and distributions (Haixin et al. 2022). In general, there is a positive correlation between microplastic concentrations and human activities, suggesting that microplastic contaminations become more severe with more frequent human activities (Scheurer and Bigalke 2018). Choi et al. (2020) found that the highest abundance of microplastics was found in soil adjacent to transportation systems (1108 particles kg^{-1}), which was dominated by black styrene-butadiene rubber fragments, and the least abundance of microplastics was found in forest soil (160 particles kg^{-1}). The results were attributed to soil adjacent to transportation systems being more directly affected by human activities, but forest soil was the opposite. Several studies identified the differences in microplastic shapes and sizes among different land use types of soil. For example, in China, fibers and large particle sizes (1–5 mm) of microplastics were abundant in cereal crops soil, and fragment shapes and pony-size microplastics (below 0.2 mm) were dominated in economic forest soil (Wang et al. 2021a). In Mu Us Sand Land, the abundance of fragments and fibers in woodland soil was significantly higher than that of grassland (Ding et al. 2021).

Migration and Degradation of Microplastics in Soil

Migration of Microplastics in Soil

The migration behavior of microplastics in soil is highly complicated (Fig. 3). The microplastics in surface soil are migrated through surface runoff and wind (Guo et al. 2020; Nizzetto et al. 2016a). The microplastics in the deeper soil are horizontally or vertically moved in soil pores with soil

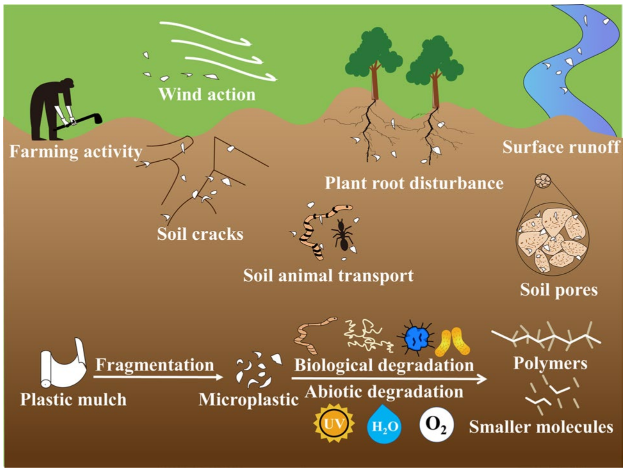

Fig. 3 Migration and degradation of microplastics in soil environments

water (Rillig et al. 2017a), soil animal transport (Rillig et al. 2017b), plant roots bioturbation (Gabet et al. 2003), farming activities (Rillig et al. 2017a), etc. The current research mainly focuses on soil pores and bioturbation. The environmental behavior of microplastics in soil and their effects on food chain and ecosystems should be investigated intensively on global scale in the future.

Soil is a porous media, and microplastics can migrate to the lower layer along with the soil pores. Liu et al. (2019b) used the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory to explain the migration behavior of microplastics in porous media and found that the migration and adsorption processes of microplastics could be enhanced with the aging of microplastics. Wang et al. (2022b) found a strong affinity for the attachment behavior of microplastics onto soil, and the dominant mechanisms of attachment behavior were electrostatic interaction and physical trapping. In addition, microplastic properties (such as particle size, shape, type, and surface chemistry) and physicochemical properties of soil (such as soil pH, ionic strength, mineral composition, cation type, organic matter type and concentration, soil mechanical composition, liquid velocity, and surface roughness) have been proven to play critical roles in determining the migration behavior of microplastics (Hou et al. 2020; Ren et al. 2021; Tan et al. 2021). In general, large porous medium particle sizes, small-sized microplastics, high soil pH, low ionic strength, high flow rates, the addition of fulvic acid, and wet-dry cycles can facilitate the transport of microplastics in porous media (Gao et al. 2021b; Hou et al. 2020; O'Connor et al. 2019; Ren et al. 2021).

Microplastics are used as carriers of heavy metals and organic pollutants to co-transport in porous media. On the one hand, co-transport contaminants affect the mobility of microplastics. On the other hand, microplastics also affect the migration of co-transport contaminants in porous media (Ren et al. 2021). Hu et al. (2020) conducted the co-transport of naphthalene with polystyrene nanoplastics (PSNP) in saturated sand columns and found that the existence of PSNP markedly enhanced the mobility of naphthalene at low ionic strength, but the existence of naphthalene decreased the mobility of PSNP, which was attributed to the charge-shielding effect. Li et al. (2019) investigated the co-transport behavior of goethite and hematite particles with different-sized PS latex microplastics in porous media. They found that the transport behavior depended upon the sizes of PS latex microspheres with no effects by 2 μm microplastics, moderately increased transport by 0.2 μm microplastics, and dramatically enhanced transport by 0.02 μm microplastics.

These studies provide new insights into the migration of microplastics in environments and afford important references for the control of microplastics in soil ecosystems. There are many transport potential ways of microplastics in soil, determining the proportion of each pathway is thus crucial for predicting their ecological risks in soil, which favors optimizing risk models and implementing more targeted monitoring and programs (Qi et al. 2020a).

Degradation of Microplastics in Soil

The degradation of microplastics can be divided into abiotic degradation and biological degradation (Fig. 3). Abiotic degradation mainly includes photodegradation, chemical degradation, and thermal degradation (Liu et al. 2022a), which leads to chain scission and crosslinking of plastics (Gewert et al. 2015; Malešič et al. 2005). Most plastic degradation studies have been conducted in the laboratory because of the slow degradation rate in natural environments. Cai et al. (2018) indicated that UV irradiation and oxygen were the important factors that affected the photo-oxidative degradation of plastic pellets. According to Jiao et al. (2020), plastic litters (such as PE, PP, and PVC) were successfully photo-converted into CH_3COOH based on the mechanism of photoinduced cleavage and coupling of C–C bond. A new study found that PS aging could be accelerated at high temperatures, and the adsorption capacity of PS increases significantly with the increment of aging degree (Ding et al. 2020a). Furthermore, the degradation rate of smaller microplastics was faster than that of medium and large plastics, due to the higher surface to volume ratio.

Conventional non-degradable microplastics with high chemical stability are extremely slow in natural degradation. Commercial PP film is cultured in soil for 12 months and weight loss only 0.4% (Arkatkar et al. 2009). More than 1 year is required to completely degrade biodegradable plastic mulching residues in the wild environments (Ghimire et al. 2020). In addition, many anthropogenic influences also affect the degradation of microplastics in soil. For instance, a new broad-spectrum fungicide prothioconazole has a positive effect on the degradation of microplastics, which promotes the degradation of the microplastics and inhibits the adsorption of Cr, As, Pb, and Ba by microplastics and augments the adsorption of Cu (Li et al. 2020b). Moreover, composting treatment is an effective disposal method for biodegradable plastics because of higher microbial enrichment and higher temperature in the composting process (Sintim et al. 2020).

Plastics are well known to be degraded slowly and thus persist in environments. According to the current production rate and degradation level of plastics, scholars estimated that the weight of plastics in marine environments would exceed that of fish in 2050 (Hong and Chen 2019). Moreover, harmful volatile organic compounds can be released from oxidative photo-degraded plastic fragments (Lomonaco et al. 2020). Therefore, biodegradation with ecofriendly nature and mild reaction conditions has become the most optimal degradation method and a hotspot in agricultural environments in recent years. Soil is rich in microorganisms because it gives the microbes more available energy and better efficiency in temperature retention. Therefore, biodegradation is the most important degradation mechanism in soil (Liao and Chen 2021). Several studies have revealed the biodegradation of plastics by soil animals (Song et al. 2020; Yang et al. 2020). For example, land snails *Achatina fulica* were capable of biodegrading PS (Song et al. 2020), and earthworms *Eisenia fetida* could break down PLA (Wang et al. 2022a). Microorganisms also have the ability to degrade plastics, and most of the plastic-degrading microorganisms are isolated from soil (Orr et al. 2004; Pranamuda et al. 1997). Genera *Enterobacter*, *Bacillus*, and *Pseudomonas* are the common bacteria for the biodegradation of plastics (Mohan et al. 2016; Shah et al. 2016, 2013). Apart from microorganisms, enzymes for degrading plastic are also an important research direction in plastic biodegradation, and some enzymes have been isolated and identified. Lu et al. (2022) successfully developed a robust and active PET hydrolase using a machine learning algorithm, and some PET products were all fully degraded by PET hydrolase within 24 h.

Analysis Methods of Microplastics in Soil

To date, the investigations on microplastics are considerable in aquatic environments, but relatively few in soil environments. The analysis methods of microplastics in soil mainly reference the relevant methods for analyzing microplastics in sediment (Chae and An 2018). Nevertheless, the research of soil microplastics proves more difficult and complex because the soil texture and aggregate structure have a significant effect on the flotation to a certain extent, and the organic matters and refractory compounds in soil interfere with the identification of microplastics (Du et al. 2020). Indeed, no standardized measurement guidelines for quantifying soil microplastics have been developed and enacted (Zhang et al. 2022b).

The routine analysis protocol for soil microplastics includes sample collection, sample drying and sieving separation, extraction, and quantitative and qualitative analysis of microplastics in soil (Fig. 4). A typical process of analysis of microplastics in soil is summarized as follows: (i) the pretreatment of soil samples; (ii) density separation; (iii) digestion of organic matter attached to the microplastics; (iv) visual identification of potential microplastics under a microscope, and then verified by infrared spectrometry and Raman spectroscopy (Masura 2015; Razeghi et al. 2021).

Along with the progress of related technologies, several advanced analysis methods appeared in the analysis protocol for soil microplastic analysis. Fluorescence staining is a quantification method for microplastic analysis using fluorescence dyes. Fluorescence dyes preferentially adsorb onto plastic particle surfaces and emit fluorescence. After rendering them distinguish from natural materials, scholars can easily identify potential microplastics through fluorescence microscopes (Maes et al. 2017). However, some common biological materials can also be fluorescence stained by fluorescence dyes but fail to be eliminated by digestion (Stanton et al. 2019). Consequently, using fluorescence staining alone results in a maximum 100% overestimation of microplastics,

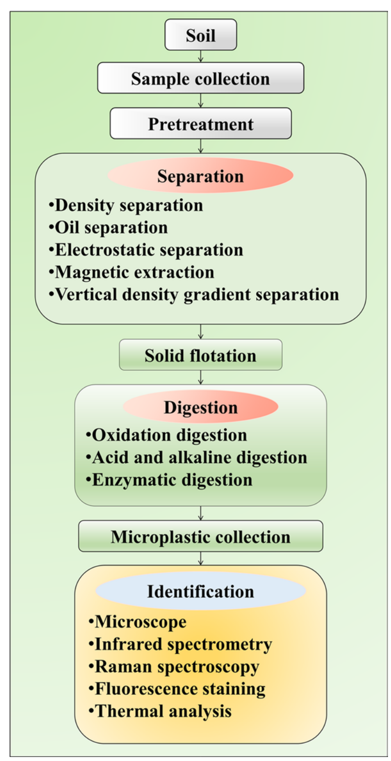

Fig. 4 Schematic diagram of analysis and detection methods for microplastics in soil

and a combined method of μ-FT-IR and fluorescence staining is encouraged in future studies (Li et al. 2018a). Thermal analysis is a straightforward, validated, and rapid method of microplastic identification that identifies polymer according to its degradation products. Besides, each polymer has characteristic degradation products and indicator ions that can be used to identify and quantify (Dumichen et al. 2017). Unfortunately, these techniques are limited by particle sizes and interfering substances, which destroy the color, size, and shape information of the microplastics, thus, subsequent analyses are inadvisable (Penalver et al. 2020). Metal labeling technique is an advanced analytical technique that enables the tracing of microplastics in any environmental media. Although metal labeling technique cannot directly measure microplastics already present in natural environments, it can define as key parameters for microplastic interactions and transfers in environments (Mitrano et al. 2019).

Ecological Effects of Microplastics in Soil

Impacts of Microplastics on Soil Physical and Chemical Properties

As well known, considerable plastics in soil can destroy soil construction and harm soil physical and chemical properties. Plastics change the water-holding capacity of soil, reduce the infiltration of rainwater and irrigation water, seriously hinder soil water and solute transport, and may lead to hypoxia (Wang et al. 2015). Furthermore, plastics also destroy soil aggregate structure, and reduce the soil aeration and water permeability, resulting in soil degradation, such as the increase in soil compaction and the decrease in soil porosity, finally affecting the growth of plants and microorganisms (Jiang et al. 2017; Zeng et al. 2013; Zhang et al. 2018a). Global meta-analysis showed that the plastic mulch had multiple negative impacts on soil properties, including soil water evaporation capacity (at the mean rate of – 2% for every additional 100 kg hm^{-2} of film residue), soil water infiltration rate (– 8%), soil organic matter (– 0.8%), and soil available phosphorus (– 5%) (Gao et al. 2018).

In contrast to macroplastics, microplastics can be integrated into soil aggregates and have a significant impact on the structure and function of soil (Machado et al. 2018b; Qi et al. 2020b). In farmland soil of lakeshore in the Dianchi Lake basin, 72% of the microplastics are combined with soil aggregates, and the remaining 28% are dispersed in the soil (Zhang and Liu 2018). Due to the influence of environmental components, microplastic types, and abundance, the relationship between soil aggregates and microplastics is complex. Zhang et al. (2019a) showed that PES microfibers (average length of 2.65 mm) increased the formation and stability of water-stable large macroaggregates (above 2 mm) in the pot experiment but not in the field experiment, and the water stability of soil aggregation induced by microplastics was enhanced after 6 dry–wet cycles. This finding is not in line with a previous study reporting that soil containing polyacrylic fibers (average length of 3756 μm) and PES fibers (average length of 5000 μm) displayed a marked decrease in water stable aggregates content with increasing microplastic concentrations (Machado et al. 2018b). A study in the Dian Lake basin suggested that the microplastic content in soil water stable microaggregates of 0.05–0.25 mm was significantly higher than that of water stability of aggregates with above 2 mm and 0.25–2 mm sizes (Zhang and Liu 2018). This implies that microaggregates with high microplastic content are difficult to be agglomerated into large agglomerates and microplastics may harm soil structure formation. Moreover, microplastics also affect soil bulk density and pore size distribution. Microplastics reduce soil bulk densities which put down to the lower density of microplastics compared with soil particles (Machado et al. 2019). Zhang et al. (2019a) found that the PES microfibers significantly decreased volumes below 30 μm pores and inversely increased the volume above 30 μm pores.

Under the long-term action of soil environments, the surface of microplastics is gradually rough, the specific surface area increasing, and the adsorption capacity significantly enhancing (Horton et al. 2017). On the one hand, the process of nutrient cycling in soil ecosystems can be affected by the adsorption of microplastics. Microplastic addition increases the nutrient contents of soil dissolved organic matter, and thus stimulates the enzymatic activity, activates the pools of organic C, N, and P, and promotes the accumulation of dissolved organic C, N, and P. Moreover, the presence of microplastics promotes the migration of nutrient elements between plants and soil (Liu et al. 2017). On the other hand, microplastics act as a carrier for the transport and transformation of pollutants. Presently, persistent organic pollutants (Huffer et al. 2019; Liu et al. 2019a; Rachman 2018; Wang et al. 2019b), heavy metals (Wang et al. 2019a; Yang et al. 2019), additives (Groh et al. 2019; Hahladakis et al. 2018), and antibiotics (Li et al. 2018c; Sun et al. 2018) have been detected on the surface of microplastics in soil. They are absorbed by microplastics and spread in the soil with the migration of microplastics, and have a synergistic effect with microplastics thus posing a greater risk to soil safety and health. Although some studies already show the effect of microplastics on the migration and degradation of soil pollutants, the related issues such as their promotion or inhibition of soil material circulation and their action mechanism are still unclear and need to be resolved urgently.

There is still a limited number of studies addressing the effects of microplastics on soil structure and function, and the behavior and mechanism of microplastics in soil are still essentially unknown at this time. Moreover, the structure of soil aggregates is complex, in-depth studies are required to verify whether the effect of microplastics on soil can be negative or not.

Impacts of Microplastics on Soil Microorganisms

Soil microorganisms are one of the most active factors in soil. Some studies have paid attention to the responses of soil microorganisms to microplastics (Table 2). As shown in Table 2, we found that microplastics influenced negatively, neutrally, or positively on soil microorganisms. The impact of microplastics on soil microbial communities is shown to be selective (Zhang et al. 2021). Several previous studies have shown that PE increased the abundance of *Actinobacteriota* but decreased that of *Proteobacteria* (Li et al. 2022a; Ren et al. 2020). Fei et al. (2020) reported that PE increased the abundance of nitrogen cycling bacteria (*Betaproteobacteriales* and *Pseudomonadales*), which confirmed that PE probably affected soil nitrogen cycling (Li et al. 2022a; Ren et al. 2020). These conflicting results suggest that the impacts of microplastics on soil microorganisms have not yet been a uniform conclusion.

Microorganisms can be adsorbed on the surface of microplastics for a long time to form biofilms and produce a unique bacterial community (Harrison et al. 2014; Zettler et al. 2013). This indicates that microplastics are a distinct habitat for soil microorganisms (Ya et al. 2021; Zhang et al. 2019b). Zhang et al. (2019b) demonstrated that microplastics in cotton fields were colonized by numerous microorganisms, which significantly differed in structure from those in ambient soil and plant litter. Bacterial community diversity, composition, and structure are also affected by microplastic amounts and types (Li et al. 2022a; Seeley et al. 2020). Unique bacterial communities were found on microplastics, which could provide potential hosts of antibiotic resistance genes (ARGs). Compared to the waterbody, fewer studies have limited comprehensive understanding of ARGs on soil microplastics (Liu et al. 2021). Zhu et al. (2022a) found

Table 2 Effects of microplastics on soil microorganisms

Polymer type	Concentration	Size	Effects	Reference
PE	18% (w/w)	–	*Actinobacteria* and fungi abundance increased; soil bacterial diversity decreased	Gao et al. (2021a)
PE	0.2% (w/w)	0.03 mm	Pathogenic microorganisms abundance increased; microbial diversity decreased	Li et al. (2021a)
PS, PLA	1% (w/w)	150–180 μm	The alpha diversity increased	Sun et al. (2022)
PU	1% (w/w)	4.28 mm	*Firmicutes*, *Bacteroidetes*, *Verrucomicrobia*, and *Fibrobacteres* abundance increased	Lian et al. (2021)
PVC	1% (w/w)	< 0.9 mm	*Ramlibacter*, *Bradyrhizobium*, and *Luteimonas* abundance increased	Yan et al. (2021)
PE	2% (w/w)	150–250 μm	*Acidobacteria* abundance increased; Shannon index increased	Rong et al. (2021)
PE	7% (w/w)	150–250 μm	*Acidobacteria* abundance increased; Shannon index decreased	Rong et al. (2021)
PHAs	10% (w/w)	–	*Acidobacteria* and *Verrucomicrobia* abundance increased; the alpha diversity increased	Zhou et al. (2021a)
PVC	6.75, 33.75 ($g\ m^{-2}$)	20 mm	Shannon–Weaver and Simpson indices decreased	Wang et al. (2016)
PE	1% (w/w)	678 μm	*Sphingomonadaceae* and *Xanthobacteraceae* abundance declined; *Burkholderiaceae* abundance increased;; bacterial diversity decreased	Fei et al. (2020)
PE, PS, PP	1% (w/w)	180–200 μm	Shannon and Chao indices decreased	Yu et al. (2021a)
PE, PS, PA, PLA, PBS, PHB	0.2%, 2% (w/w)	39–80 μm	*Ktedonobacterales* abundance declined; *Rhizobiales* abundance increased; the alpha diversity of bacterial decreased	Feng et al. (2022)
PS	2% (w/w)	32.6 nm	Soil microbial biomass decreased	Awet et al. (2018)
PE	28% (w/w)	< 100 μm	*Actinobacteria* replaced *Proteobacteria* as the dominant phylum; Shannon indices decreased	Hou et al. (2021)
PE	5% (w/w)	< 150 μm	*Acidobacteria*, *Nitrospirae* and *Bacteroidetes* abundance declined	Ren et al. (2020)
PS,	0.5% (w/w)	330–640 μm	No significant effect in Shannon and Simpson index	Xu et al. (2021)
PE, PVC, PET	1% (w/w)	< 2 mm	No significant effect in soil microbial function	Judy et al. (2019)
PLA	2% (w/w)	20–50 μm	No significant effect in bacterial communities	Chen et al. (2020a)
PE, PP	1% (w/w)	200–630 μm	No significant effect in microbial community	Blocker et al. (2020)
PE	2, 10, 15 ($g\ m^{-2}$)	37.13 μm	No significant effect in microbial communities	Lin et al. (2020)
PE	0.1%, 1%, 10% (w/w)	100–154 μm	No significant effect in *Arbuscular mycorrhizal fungal* diversity	Yang et al. (2021d)

Note: "–" represents unknown

that ARGs were enriched in the biofilm compared to the soil, which suggested soil biofilms were hotspots of ARGs. Wang et al. (2021b) also found that microplastics were the hotspot of *intl1* gene in soil and significantly increased the total relative abundance of ARGs.

Furthermore, microplastics can indirectly affect the life activities of soil microorganisms by altering soil physical, chemical, and aeriferous properties (Bandopadhyay et al. 2018; Veresoglou et al. 2015; Zhang et al. 2021). Many studies have demonstrated that there was a positive and negative correlation between soil physicochemical properties and the abundance of various bacteria (Li et al. 2022a; Song et al. 2018). Hou et al. (2021) showed that PE addition increased the relative abundance of *Actinobacteria* and reduced the relative abundance of *Proteobacteria* through soil bulk density.

Impacts of Microplastics on Soil Fauna

Microplastics accumulate in soil fauna through feeding behavior and have a certain toxic effect on soil fauna (Zhu et al. 2019). Studies on earthworms have shown that microplastics could affect the growth, reproduction, and survival rate of earthworms, and after entering the body. They will destroy male reproductive organs, inhibit spermatogenesis, cause intestinal damage, and affect eating and excretion. (Kwak and An 2021; Lwanga et al. 2016, 2017a; Rodriguez-Seijo et al. 2017). Studies on nematode *Caenorhabditis elegans* showed that microplastics inhibited survival rates, body length, and reproduction (Le et al. 2018). Moreover, exposure to microplastics reduces calcium levels of nematode *Caenorhabditis elegans* but increases expression of the oxidative stress response genes *gst-4* and causes intestinal damage and oxidative damage (Lei et al. 2018). Yu et al. (2020) showed that the toxicity of PS microplastics on nematode *Caenorhabditis elegans* might result from oxidative stress and intestinal injury. Notably, the existing studies mainly focus on model animals, and other soil fauna is rather limited and warrants further research.

The toxic and harmful substances attached to the microplastic surface harm soil fauna and result in pathological changes and even death of soil fauna. Chemicals leaching from microplastic additives, such as phthalates and bisphenol A, may also damage the endocrine system of vertebrates through estrogenic activity (Machado et al. 2018a). Huang et al. (2021) demonstrated that the joint toxicity of microplastics and cadmium on earthworms caused oxidative stress and sperm damage and inhibited the growth and reproduction of earthworms. Furthermore, microplastics can indirectly affect the life activities of soil fauna by altering soil physical and chemical properties (Rillig 2012). Complex systems and wide distribution of soil fauna restrict the further study of soil animal groups. However, a deeper exploration is prerequisite for evaluating the overall impact of microplastic pollution on the soil ecosystems.

Impacts of Microplastics on Plants

Microplastics brought out negative effects on the growth of wheat (*Triticum aestivum* L.) (Bandmann et al. 2012; Kalcikova et al. 2017; Qi et al. 2018; Ren et al. 2022a), barley (*Hordeum vulgare* L.) (Li et al. 2021b), broad bean (*Vicia faba*) (Jiang et al. 2019), common bean (*Phaseolus vulgaris* L.) (Meng et al. 2021), cabbage (*Brassica chinensis* L.) (Yang et al. 2021c), water celery (*Lepidum sativum* L.) (Bosker et al. 2019; Pignattelli et al. 2020), perennial ryegrass (*Lolium perenne* L.) (Boots et al. 2019), pumpkin (*Cucurbita pepo L.*) (Colzi et al. 2022), onion (*Allium fistulosum* L.) (Machado et al. 2019), and rice (*Oryza sativa* L.) (Wu et al. 2020). Phytotoxicity caused by microplastics may depend upon many variables, including polymer type, presence of additives, surface charge of plastics, and dose (Larue et al. 2021). For instance, Ren et al. (2022a) indicated that PLA fragments and PS beads significantly reduced plant height and base diameter, which adversely affected the growth of wheat seedlings. In another study, PES fibers induced the strongest effects on Allium fistulosum traits compared to PA beads and microparticles of high density PE (Machado et al. 2019). Sun et al. (2020) addressed that positively charged nanoplastics were uptaken less than negatively charged nanoplastics in root tips, but a higher accumulation of reactive oxygen species induced by these nanoplastics and more toxic to Arabidopsis thaliana. Besides, leaching of additives from plastics can also cause toxicity to plants (Gunaalan et al. 2020). However, microplastics can also affect different plants positively or nonsignificantly (Chen et al. 2022). For example, microplastics increase soil enzyme activity and nutrient turnover, and then affect plant growth (Zhou et al. 2021a). In the study of Liu et al. (2022c), the PE microplastic addition improved the nutrient uptake (NH_4^+-N and NO_3^--N) by wheat.

The impacts of microplastics on plants are generally indirect. As mentioned above, microplastics have various impacts on the carbon cycling processes, rhizosphere microbial community, and soil physicochemical properties, thus affecting the growth and development of plants (either positive or negative or nonsignificant) (Chen et al. 2022; Rillig et al. 2021). For example, *Bacteroidetes* of wheat rhizosphere used PHBV as a source of carbon resulting in a stimulation of nutrient efficiency (Zhou et al. 2021a); PS beads and degradable mulching film fragments enhanced abundance of the pathogen (*Fusarium* and *Alternaria*) to wheat, which was the dominant genus in the rhizosphere and adversely affected the crop (Ren et al. 2022b); PE powders decreased the diversity of rhizosphere soil bacterial communities (Zhu et al. 2022b). Lozano and Rillig (2020) indicated that the positive effect on shoots and root containing PES microfibers was related to the reduction of soil bulk density and the improvement of aeration.

Conclusion and Perspectives

This paper reviews the current situation and ecological effects of microplastic pollution in soil. We have come to the following conclusions: (1) soil is a reservoir of microplastics, exhibiting a wide distribution and high abundance; (2) distribution of microplastics in soil displays spatial heterogeneity, which may be affected by land use patterns and human activity intensity; and (3) microplastics can affect soil physical, chemical, and biological properties through several mechanisms, leading to different ecological effects.

More recently, research on soil microplastics has been gradually carried out, and some progress has been achieved, but the relevant research is not sufficient and systematic, and still requires filling the knowledge gap. The investigation of soil microplastics in the future might be carried out from the following aspects:

Microplastics have a wide distribution and high abundance in soil. Therefore, there is an urgent need for large-scale effective monitoring projects to evaluate the source and distribution of microplastics around the globe, and quantify the contribution of various natural processes and human activities to soil microplastic pollution. Metal labeling technique is an effective means of defining key parameters for microplastics transfer in environments. However, there is a lack of standardized processes and methods for analyzing and detecting microplastics in soil. To further investigate and comparably analyze the results, it is urgent to establish a set of standardized processes and methods for the analysis and detection of microplastics in soil, and a new systematic classification of microplastics with different shapes, sizes, and components.

The impact of microplastics on soil is complex, but related research is still scarce, and fails to draw a valid result at present. In the future, the categorized studies should be carried out from the aspects of soil types, microplastic types, and abundance to explore the effects of microplastics on soil physicochemical properties and nutrient cycling. Microplastics also have compound pollution on soil when microplastics act as vectors for other toxic pollutants (e.g., heavy metal ions, organic pollutants, antibiotics). However, the mechanism of synergetic or antagonistic effects of microplastics and pollutants on soil needs to be elucidated. Furthermore, future research should determine biological toxicity and dosage effects of microplastics on soil organisms and plants. The complexity of soil environments is critical to the no-sole action of microplastics, thus, it is necessary to systematically study the compound effects of microplastics and additives or other substances on soil.

The long-term accumulation of microplastics in soil will negatively affect plants. In particular, nanoplastics (microplastics with a diameter of below 1 μm) are more prone to enter biological cells and demonstrate stronger ecological and toxic effects. We know little about their pollution sources, transport trajectories, and bioaccumulation. Future studies should explore in-depth the microplastic-plant interactions and migration mechanisms of microplastics in the soil–plant system. The rare-earth-metal labeling strategy is an effective means of quantifying and visualizing microplastics within the plants and should be widely used in the future.

Biodegradation is an ideal removal way of microplastic in soil. On the basis of existing biodegradation studies, further studies are required to illustrate the effects of microplastic degradation in soil ecosystems and its mechanism. High-throughput sequencing technology is an effective means of exploring the effects of microplastics in soil ecosystems. Future research should cover how biodegradable microplastics affect soil ecosystems.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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