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Review

Plastic mulching, and occurrence, incorporation, degradation, and impacts of polyethylene microplastics in agroecosystems

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ABSTRACT

Polyethylene microplastics have been detected in farmland soil, irrigation water, and soil organisms in agroecosystems, while plastic mulching is suggested as a crucial source of microplastic pollution in the agroecosystem. Plastic mulch can be broken down from plastic mulch debris to microplastics through environmental aging and degradation process in farmlands, and the colonization of polyethylene-degrading microorganisms on polyethylene microplastics can eventually enzymatically depolymerize the polyethylene molecular chains with CO_2 release through the tricarboxylic acid cycle. The selective colonization of microplastics by soil microorganisms can cause changes in soil microbial community composition, and it can consequently elicit changes in enzyme activities and nutrient element content in the soil. The biological uptake of polyethylene microplastics and the associated disturbance of energy investment are the main mechanisms impacting soil-dwelling animal development and behavior. As polyethylene microplastics are highly hydrophobic, their presence among soil particles can contribute to soil water repellency and influence soil water availability. Polyethylene microplastics have been shown to cause impacts on crop plant growth, as manifested by the effects of polyethylene microplastics on soil properties and soil biota in the agroecosystems. This review reveals the degradation process, biological impacts, and associated mechanisms of polyethylene microplastics in agroecosystems and could be a critical reference for their risk assessment and management.

1. Introduction

Polyethylene (PE), the most widely used plastic polymer, is a synthetic polymer of high molecular weight containing a structure of linear saturated hydrocarbon, which can be expressed as -$[CH_2\text{-}CH_2]_n$- (Ahmad and Rodrigue, 2022; Clere et al., 2022; Zhong et al., 2018). PE accounts for around 30 % of the total plastic polymers' demand, and its annual global production is approximately 140 million tons (Plastics Europe, 2018). Polyethylene is applied to various products from carry bags and piping to the construction of fuel storage tanks (Restrepo-Flórez et al., 2014). Particularly, polyethylene is also used in considerable quantities in agriculture for greenhouse construction or directly applied on the soil surface as mulching films (Koutny et al., 2006).

Due to the enormous production and limited recycling rate of polyethylene products, polyethylene plastic waste has become an environmental issue, with most polyethylene plastic are still released into the environment (He et al., 2018). In farmland soil, farming activities, solar UV, wind, rain, irrigation, soil-dwelling animal chewing, and microbial degradation can cause polyethylene plastics, e.g., polyethylene plastic mulch, to fragment and breakdown into polyethylene microplastics with a size smaller than 5 mm (Cao et al., 2022; Chen et al., 2021; Liu et al., 2022; Napper and Thompson, 2019; Tirkey and Upadhyay, 2021; Wang et al., 2020). In recent years, polyethylene microplastics have been detected in farmland soil, irrigation water, and soil organisms in

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agroecosystems (Crossman et al., 2020; Helcoski et al., 2020; Kim and An, 2020; Kim et al., 2021; Piehl et al., 2018; Rezaei et al., 2019; Wang et al., 2019; Weber and Opp, 2020; Zhou et al., 2020). In addition, more and more studies show that polyethylene microplastic contamination can impact soil properties, soil biota, and crop plants (Chen et al., 2020; Fei et al., 2020; Kim and An, 2020; Qi et al., 2018; Zhang et al., 2021). The contaminant polyethylene microplastic is of increasing concern (Chen et al., 2020; El-Sherif et al., 2022; He et al., 2018).

Up to now, although several authors have reviewed the distribution of polyethylene microplastics and its effects on biota in different environments (El-Sherif et al., 2022; Kumar et al., 2022; Ya et al., 2021), the systematic knowledge of polyethylene microplastics in agroecosystems is very limited. It is still a big necessity to explore pollution characteristics and ecological risk assessment of polyethylene microplastics in agroecosystems. In the present review, the authors have provided an overview of recent progresses in pollution detection, degradation process, and ecological impacts of polyethylene microplastics in agroecosystems and also suggest the crucial challenges and prioritized research in the future. Moreover, this review has also highlighted the environmental aging and degradation process from plastic mulch debris to polyethylene microplastics in agroecosystems, as well as biofilm formation and biodegradation of polyethylene microplastics in agroecosystems. This review sheds light on the contribution of plastic film as a plastic source to microplastic pollution, which previous literature has been lacking.

In this review, a search using the strings was performed on Web of Science: polyethylene microplastic AND distribution AND farmland; polyethylene microplastic AND aging; polyethylene microplastic AND biodegradation; polyethylene microplastic AND soil properties; polyethylene microplastic AND effect AND soil microorganism; polyethylene microplastic AND uptake AND soil organism; polyethylene microplastic AND effect AND soil organism; polyethylene microplastic AND effect AND behavior; polyethylene microplastic AND effect AND plant. Google Scholar was also used to screen polyethylene microplastic and environmental fate/degradation process/ecological impacts-related studies individually to ensure the comprehensiveness of the data. The publications as close as possible to the most recent five years (2018–2022) were identified, and the most relevant publications to the subject of this study were selected. The information about polyethylene microplastic used in related studies was collected and analyzed, including occurrence, distribution, aging process, and biodegradation of polyethylene microplastic. The effects and impacts of polyethylene microplastic on soil microorganisms, soil organisms, and plants were also collected, summarized and compared. The collected information is further integrated and synthesized into the below contents.

2. Plastic mulching as the major source of polyethylene microplastics in agroecosystems

Agroecosystems are the basis for human food production; all elements of agroecosystems are closely related to the life and work of people (Ramankutty et al., 2018). Plastic mulch, usually one to two meters in width, is often used with drip irrigation (Tiwari et al., 2014) or furrow irrigation (Ingman et al., 2015). Plastic mulch is used in agriculture to effectively suppress weeds, reduce the evaporation of soil water, make the soil maintain appropriate temperature and humidity, and promote crop precocity and increase yields (Kasirajan and Ngouajio, 2012; Li et al., 2022). The use of plastic mulch is increasing, and its use can be found across farming scales (Ranjan et al., 2017; Xiong et al., 2019).

Polyethylene is either produced directly into plastic mulch or as part of a biodegradable mulch (Ranjan et al., 2017). Biodegradable mulches commercially available in agriculture are usually a blend of biobased and non-biobased ingredients (Hayes et al., 2019). Biobased ingredients of biodegradable mulches are those materials that are found in nature, such as pullulan and polylactic acid (PLA), and they can be degraded by soil organisms. Non-biobased ingredients of the biodegradable mulches are fabricated materials, e.g., polyethylene (PE), which soil organisms can hardly degrade; thus, they are not environment-friendly (Kasirajan and Ngouajio, 2012; Ranjan et al., 2017). In one example, Ohtake et al. (1998) studied PE plastic degradation in natural environments by burying PE bottles in soil for 32 years and observed signs of some minimal degradation on its surface. This suggests that it would take approximately 300 years to entirely degrade 60 μm low-density polyethylene (LDPE) films in the soil at such slow rates (Ohtake et al., 1998).

In 2020, over 2.1 million tons of plastic mulch were used in agriculture globally (Wang et al., 2022). Non-biodegradable plastic mulches are more widely used than biodegradable plastic mulches in the world due to their low cost and high tensile strength and durability (Nanda and Berruti, 2021). PE, low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and high-density polyethylene (HDPE) are some of the most commonly used non-biodegradable plastic mulches (Madrid et al., 2022). Non-biodegradable plastic mulch made from polyethylene contamination has elicited a significant environmental concern due to the continuous usage of mulch film in agriculture. The macro- ($\geq$ 5 mm) and microscopic ($<$ 5 mm) plastic pollution were introduced to the farmland by the use of plastic mulch, including the incomplete removal of plastic mulch after use (Qi et al., 2020a).

Previous studies have suggested that plastic mulching is a crucial source of microplastic pollution in terrestrial environments (Kim et al., 2021; Rezaei et al., 2019; Scheurer and Bigalke, 2018). The abundance of microplastics has a positive correlation to the history of using mulch film in agricultural farmlands (Xu et al., 2022). Mulched soils contained more significant amounts of microplastics (over 570 pieces/kg) than non-mulched soils (260 pieces/kg), implying that mulch film was the most important potential source of microplastics (Zhou et al., 2020). In addition, Meng et al. (2020) reported that the mulching duration period could also affect the distribution and accumulation of macro- and microplastics in agricultural ecosystems, and continuous mulching led to more accumulation of macroplastics than intermittent mulching under the same farming mode. The thickness of the mulch and its tensile strength will also impact how much contamination is left behind. Thin ($<$ 10 μm), LDPE can more easily fragment than thicker films. Furthermore, PE microplastics represent the vast majority of microplastics that have been detected in soil environments, indicating that microplastic contamination may mainly derive from the plastic mulching in farmlands (Crossman et al., 2020; Kim et al., 2021; Scheurer and Bigalke, 2018).

3. Occurrence and distribution of polyethylene microplastics in agroecosystems

Polyethylene microplastics, e.g., PE and LDPE, have been detected in different farmland soils in various regions around the world, including Germany, Korea, Canada, Switzerland, Iran, the USA, and China (Table 1). PE is one of the most widely found microplastics in terrestrial environments (Hüffer et al., 2019). The highest concentration of PE microplastics can reach 2000 items/kg of dry soil in the agricultural field (Kim et al., 2021). The reported smallest size of the polyethylene microplastics is 40 μm (Rezaei et al., 2019).

PE microplastics can migrate through environmental media. PE microplastics were detected in the irrigation water at a concentration of around 1–2 pieces/kg from surrounding irrigation ditches of agricultural fields (Zhou et al., 2020). Recent work has highlighted microplastics can migrate from farmland to aquatic systems through atmosphere transporting (Brahney et al., 2021; Ouyang et al., 2020). In addition to migrating in different environmental media, microplastics can also migrate in soil. Hu et al. (2021) demonstrated that the microplastic size had a linear negative correlation with soil depth. Smaller microplastic particles were easier to pass through soil pores to migrate (Hu et al., 2021).

Table 1
Distribution of polyethylene microplastics in the farmland soil.

Region	Soil sampling (depth)	Microplastics			Refs.
		Type	Size	Abundance	
Franconia, Germany	0–5 cm	PE	1–5 mm	0.7143 ± 0.7263 particles/kg	Piehl et al. (2018)
Hesse, Germany	0–2 m	LDPE	2–5 mm	1.88 particles/kg	Weber and Opp (2020)
Yong-In, Korea	0–5 cm	PE	0.1–5 mm	10–7630 particles/kg	Kim et al. (2021)
Ontario, Canada	0–15 cm	PE	< 5 mm	18–298 particles/kg	Crossman et al. (2020)
Berne, Switzerland	0–5 cm	PE	< 5 mm	0–593 particles/kg	Scheurer and Bigalke (2018)
Fars, Iran	0–10 cm	PE	40–740 μm	67–400 particles/kg	Rezaei et al. (2019)
Washington, USA	0–5 cm	PE	75 μm – 5 mm	334–3068 particles/kg	Helcoski et al. (2020)
Hangzhou, China	0–10 cm	PE	50 μm – 5 mm	~60 particles/kg	Zhou et al. (2020)
Shihezi, China	0–40 cm	PE	7 μm – 5 mm	80.3 ± 49.3, 308 ± 138.1, and 1075.6 ± 346.8 particles/kg in 5, 15 and 24 year mulching fields, respectively	Huang et al. (2020)
Alar, China	0–800 mm	PE	31 μm – 4.9 mm (0–300 mm soil layer); 1.1 μm – 1.88 mm (400–800 mm soil layer)	161.50 ± 5.20 particles/100 g (0–300 mm soil layer); 11.20 ± 1.10 particles/100 g (400–800 mm soil layer)	Hu et al. (2021)

Note. PE, polyethylene; LDPE, low-density polyethylene.

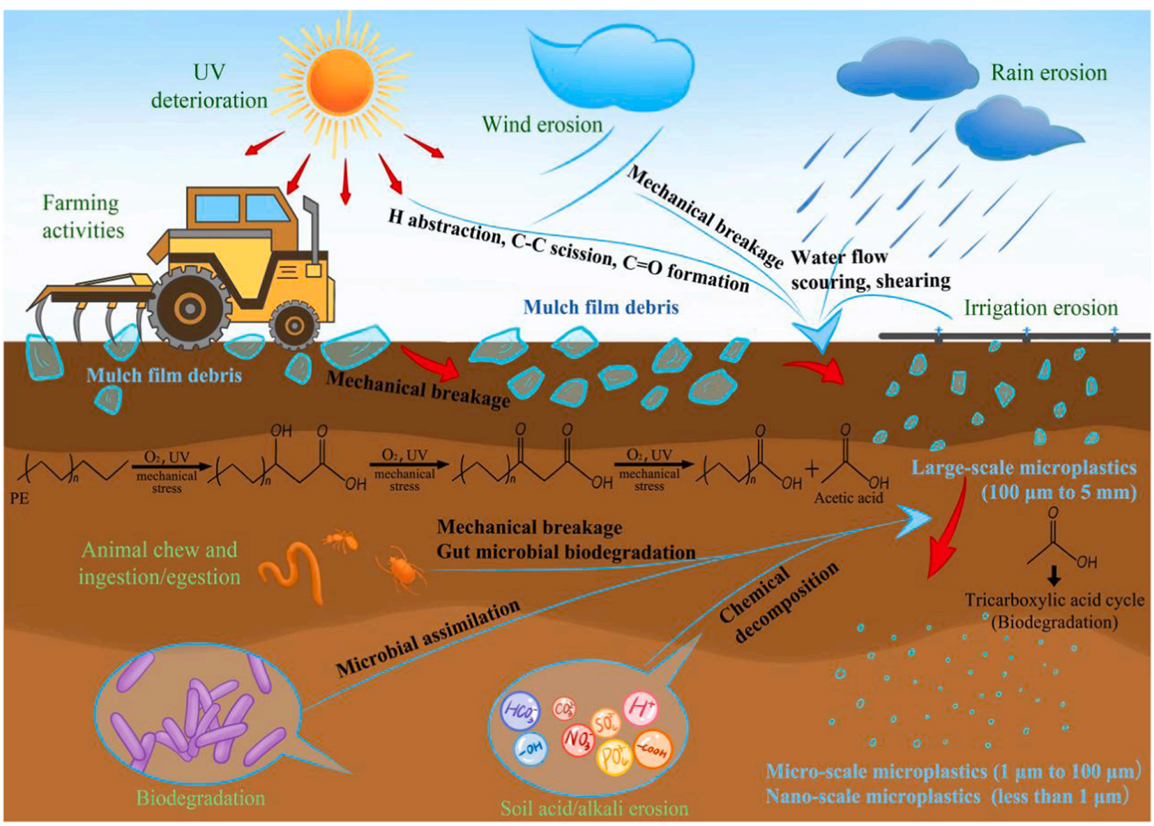

Fig. 1. An overview of degradation and aging process of polyethylene microplastics in the soil in agroecosystems. The degradation and aging process of polyethylene microplastics mainly consists of three steps (red arrows): mulch film debris is broken down into small mulch film debris, small mulch film debris is degraded into large-scale microplastics, and then large-scale microplastics are degraded into micro-scale and nano-scale microplastics. For each step, the details can be explained as (blue arrows): in plastic-mulched farmlands, the farming activities, e.g., plowing, harvesting, and mulch film recycling, can cause the production of a large amount of plastic debris; solar UV, wind, rain, and irrigation further decompose the plastic waste to microplastics with a size of less than 5 mm; meanwhile, in soil, animal chewing and ingesting, microbial degradation, and the action of soil acid and alkali can further contribute to the degradation of the mulch film debris, making the large-scale microplastics to the micro-scale and nano-scale microplastics.

4. Environmental aging and degradation process from plastic mulch debris to microplastics

In farmland soil, the farming activities, such as tillage and mulch film recycling, etc., cause the production of a large amount of plastic debris. Tillage and recycling of mulch films can cause plastics to fragment and get incorporated in the soil as well as incomplete removal. Solar UV, wind, rain, and irrigation further breakdown the mulch film debris to be large-scale microplastics (Cao et al., 2022; Chen et al., 2021; Napper and Thompson, 2019; Tirkey and Upadhyay, 2021; Wang et al., 2020). Meanwhile, the soil-dwelling animal chewing, microbial degradation, and the effects of soil acid and alkali could be further contributed to the

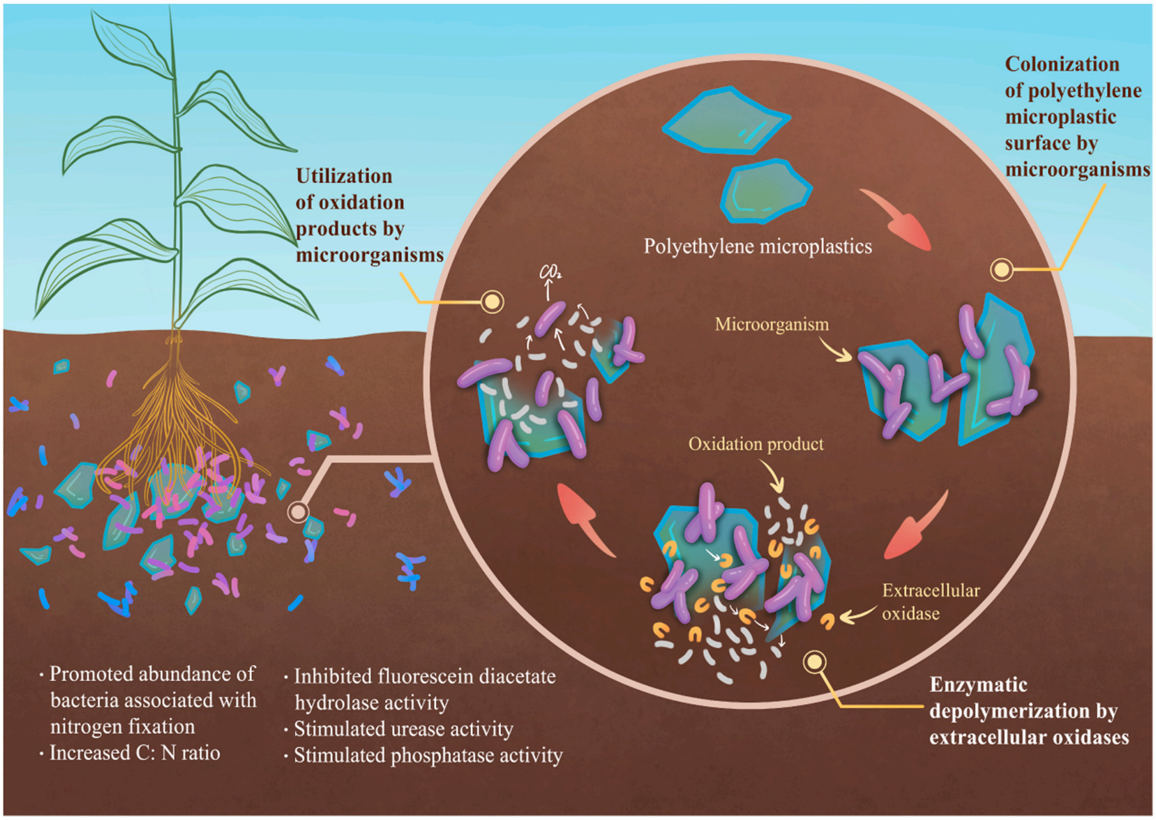

Fig. 2. Potential biodegradation pathways of polyethylene microplastic in the soil. The process of biodegradation of polyethylene microplastics can be presented in three steps (red arrows): polyethylene-degrading microorganisms colonize the film surface; microorganisms secrete extracellular oxidases for enzymatic depolymerization of the film; microorganisms uptake and utilize monomers and short oligomers of oxidation products for energy production and biomass formation with CO_2 release. The selective colonization of polyethylene microplastics by microorganisms contributes to changes in the community composition, eliciting changes in carbon and nitrogen content and enzyme activities of soil, which might cause impacts on nutrient circulation in plant rhizosphere.

Table 2
Biodegradation studies of polyethylene microplastics.

Polymers	Degradation duration	Species for degradation	Degradation performance	Ref.
PE	60 days	Bacteria: *Paenibacillus sp.*	14.70 % mass loss	Park and Kim (2019)
	30 days	Bacteria: *ligninolytic bacteria*	6.68 % mass loss	Kavitha and Bhuvaneswari (2021)
LDPE	42 days	Bacteria: *Pseudomonas sp. MMP, Acinetobacter sp. MGP1, Bacillus sp. MMP10, Bacillus sp. MGP1*	3.75 % mass loss	Kunlere et al. (2019)
	112 days	Bacteria: *Bacillus cereus strain A5*	(35.72 ± 4. 01) % mass loss	Muhonja et al. (2018)
	112 days	Bacteria: *Brevibacillus borstelensis strain B2*	(20.28 ± 2. 30) % mass loss	
	140 days	Bacteria: *Aneurinibacillus sp.*	(58.21 ± 2) % mass loss	Skariyachan et al. (2018)
	90 days	Bacteria: *Exiguobacterium sp*	(5.70 ± 0.7) % mass loss	Maroof et al. (2022)
	180 days	Bacteria: *Ralstonia sp*	39.2 % mass loss	Biki et al. (2021)
	180 days	Bacteria: *Bacillus sp*	18.9 % mass loss	
	4 weeks	Bacteria: *Acinetobacter pittii*	(26.8 ± 3.04) % mass loss	Montazer et al. (2018)
	4 weeks	Bacteria: *Phylum Actinobacteria* and *Firmicutes*	60 % mass loss	Huerta Lwanga et al. (2018)
	5 weeks	Nanoparticle-based bioremediating	64.5 % mass loss	Jayaprakash and Palempalli (2019)
HDPE	25 days	Bacteria: *Alcaligenes faecalis*	5.8 % mass loss	Tareen et al. (2022)
	140 days	Bacteria: *Aneurinibacillus sp.*	(46.6 ± 3) % mass loss	Skariyachan et al. (2018)
	28 days	Fungi: *Aspergillus flavus PEDX3*	(3.9025 ± 1.18) % mass loss	Zhang et al. (2020b)
	5 weeks	Nanoparticle-based bioremediating	44.4 % mass loss	Jayaprakash and Palempalli (2019)
LLDPE	25 days	Bacteria: *Alcaligenes faecalis*	3.5 % mass loss	Tareen et al. (2022)

Note. PE, polyethylene; LDPE, low-density polyethylene; HDPE, high-density polyethylene; LLDPE, linear low-density polyethylene.

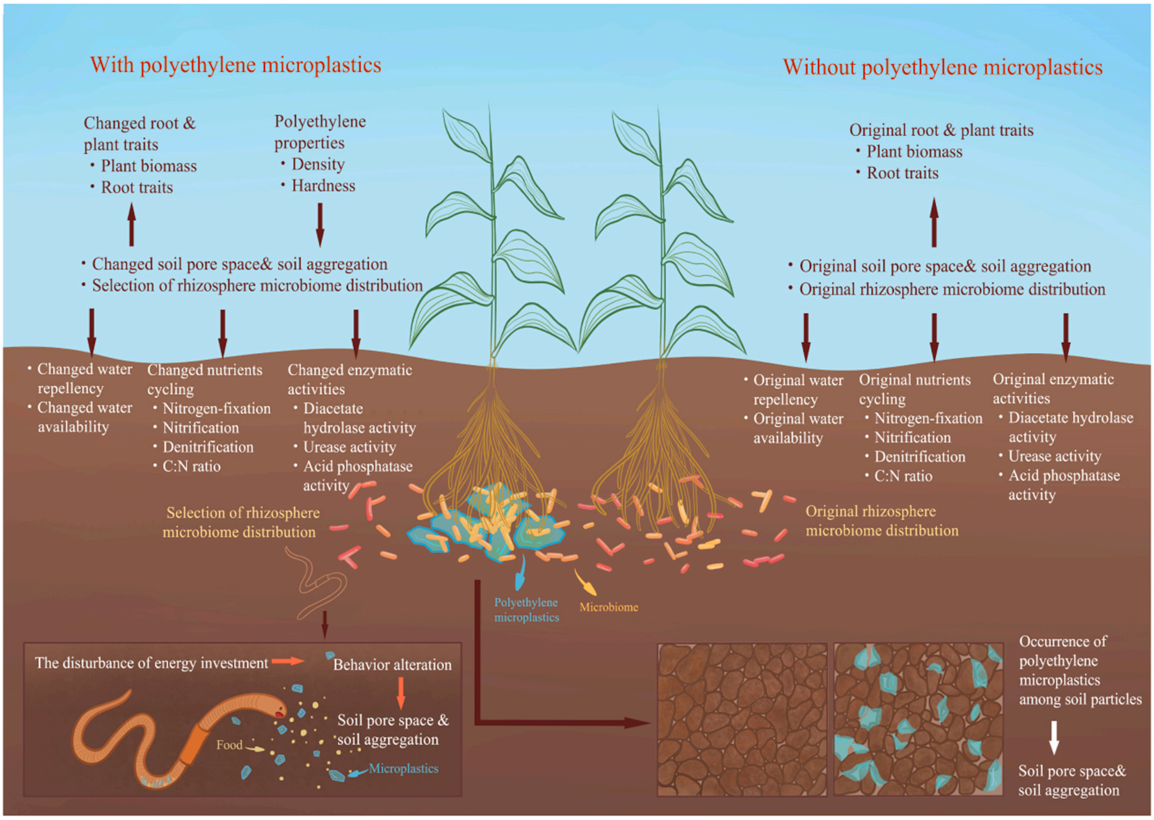

Fig. 3. Potential impacts and associated mechanisms of polyethylene microplastics on soil properties, soil biota, and plant growth can be summarized as three parts: (1) The occurrence and distribution of polyethylene microplastics contribute to the change of soil pore space and soil aggregation (white arrow). This change in soil structure can subsequently influence soil water availability; (2) The ingestion of polyethylene microplastics by soil-dwelling animals decreases the opportunity for energy gain from food as microplastics are digested but occupy the space (red arrow). This causes an imbalance in energy distribution in the animals. The disturbance of energy investment can subsequently provoke changes in feeding behavior, locomotion velocity and distance, avoidance, and other behaviors of the soil-dwelling animals, which could contribute to the change of soil pore space and soil aggregation, and subsequently influence soil water availability; (3) The selective colonization of microplastic films by microorganisms contribute to changes in the community composition in the plant rhizosphere soil, eliciting changes in nutrients cycling and the enzyme activities. The effects of polyethylene microplastics on soil properties and soil biota can eventually influence plant root traits and plant biomass (brown arrows).

degradation of the mulch film debris, making the large-scale microplastics into micro/nano-scale microplastics (Chen et al., 2021; Liu et al., 2022; Napper and Thompson, 2019; Tirkey and Upadhyay, 2021; Wang et al., 2020). Among the factors, farming activity plays a crucial role in turning large mulch film debris into small mulch film debris and bringing plastic debris from the surface to the belowground.

During the process of PE degradation, UV light radiation is the main force of H abstraction, C—C bond scission, and C═O bond formation of polyethylene molecular structure (Chen et al., 2021; Duan et al., 2022). The water flow scouring caused by rain and irrigation, as well as the mechanical breakage caused by wind, could enhance this effect. As a result, the ethylene group of mulch films is oxidized into a carbonyl or ester group, thereafter the small mulch film debris becomes large-scale microplastics (size between 100 μm and 5 mm) (Chen et al., 2021; Duan et al., 2022; Tirkey and Upadhyay, 2021). Under the ground, microbial degradation, acid/alkali erosion, as well as mechanical breakage caused by animal chewing and ingesting can promote the degradation of mulch film microplastics, decomposing the large-scale microplastics to micro-scale (size between 100 μm and 1 μm) and nano-scale (size less than 1 μm) microplastics (Chen et al., 2021; Li et al., 2019; Tirkey and Upadhyay, 2021; Wilkes and Aristilde, 2017). The content of acid and alkali reflects the pH level of the soil (Neina, 2019); the action of soil acid and alkali might accelerate or reduce the degradation of polyethylene microplastics, as pH is one of the fundamental abiotic factors for polyethylene degradation (Bahl et al., 2021; Lin et al., 2022). During the degradation of PE molecules, the alkyl radicals of PE molecules react with oxygen to form peroxy radicals, after which a hydrogen atom is extracted from the polymer chain to respond with the peroxy radical and form hydroperoxide (Ariza-Tarazona et al., 2020; Lin et al., 2022). Hydrogen atoms existing in the form of H^+ under acidic conditions (i.e., low pH) can contribute to the concentration increase of H^+ and can promote the formation of hydroperoxide (Ariza-Tarazona et al., 2020; Lin et al., 2022). Thus acidic conditions can accelerate the reaction rate (Ariza-Tarazona et al., 2020; Lin et al., 2022). On the other hand, the moisture content in soil plays a vital role in the growth of microorganisms; with an increase in moisture content, the hydrolytic cleavage of microbes would increase, and the rate of hydrolytic reaction is affected by a change in pH (Bahl et al., 2021; Lin et al., 2022). As a result, a change in pH affects the microbial growth rate, and it does affect the rate of degradation (Bahl et al., 2021; Lin et al., 2022). Studies have shown that intestinal microbiomes and ingesting behavior of some insects can contribute to the biodegradation of polyethylene (Billen et al., 2020; Mohanan et al., 2020; Yang et al., 2014; Yin et al., 2020). Bacteria identified from the gut of the insect *Plodia interpunctella* could degrade about 6–10 % of PE films (Yang et al., 2014). The co-culture of bacteria strains, *Acinetobacter sp. NyZ450* and *Bacillus sp. NyZ451*, identified from the gut of the insect *Tenebrio molitor* larvae, could remove LDPE mulching films by 18 % (Yin et al., 2020). In addition, chewing and ingesting polyethylene by insect *Tenebrio molitor* larvae could generate holes and decrease the size of polyethylene films (Billen et al., 2020). The polyethylene-degrading indication of chewing and ingesting behavior, as well as the degradation function of digestive

Table 3
Effects of polyethylene microplastics on soil-dwelling animals in agroecosystem.

Test species	Polymers	Size	Exposure dose	Effects	Refs.
Isopod (*Porcellio scaber*)	PE	183 ± 93 μm, 1367 ± 51 μm	4 mg/g food dry weight	No effects on feeding and energy reserves of isopods.	Jemec Kokalj et al. (2017)
Springtail (*Lobella sokamensis*)	PE	29 ± 4 μm, 248 ± 14 μm	1000 mg/kg soil dry weight	Decreased the mobility.	Kim and An (2019)
		< 50 μm (32 %), 50–200 μm (25 %), 200–500 μm (43 %)	0.5 %, 1 % in dry soil (w/w) (avoidance); 0.005 %, 0.02 %, 0.1 %, 0.5 %, 1 % (w/w) (reproduction); 0.5 % (w/w) (gut microbiota)	Increased avoidance rate, inhibited reproduction, and decreased bacterial diversity in gut.	Ju et al. (2019)
Springtail (Folsomia candida)	PE	2.1 ± 0.7 μm, 33.7 ± 3.4 μm, 66.0 ± 10.9 μm	10 mg/90 mg dried yeast plus 120 mL deionized water	Decreased movement velocity and distance.	Kim and An (2020)
Nematode (*Caenorhabditis elegans*)	PE	~ 70 μm	0.5, 1.0, 5.0, 10.0 mg/m^2	Decreased body length and intestinal calcium levels, increased intestinal glutathione S-transferase 4 enzyme expression, elicited reproduction inhibition (reduction of embryo number and brood size).	Lei et al. (2018)
Earthworm (*Lumbricus terrestris*)	LDPE	≤ 50 μm (40 %), 63–150 μm (60 %)	7 %, 28 %, 45 %, and 60 % w/w in plant litter dry weight	Caused more burrows.	Huerta Lwanga et al. (2017a)
		< 50 μm (50 %), 50–100 μm (27 %), 100–150 μm (23 %)	1 %, 3 %, 7 % (w/w) litter dry weight	Influenced earthworm gallery (all burrows per box) volume.	Yang et al. (2019)
	HDPE	0.92 ± 1.09 mm^2	236, 1261, and 4505 mg/kg moist soil weight	No effects on mortality or weight change.	Hodson et al. (2017)
Earthworm (*Eisenia andrei Bouche*)	PE	250–1000 mm	62.5, 125, 250, 500, 1000 mg/kg soil dry weight	Caused histopathological damages and immune system responses.	Rodriguez-Seijo et al. (2017)
Earthworm (*Eisenia fetida*)	LDPE	≤ 300 μm	1 %, 5 %, 10 %, and 20 % (w/w) soil dry weight	Changed activity of antioxidase.	Wang et al. (2019)
		5 mm, 250 μm – 1 mm	5 mm: 8 particles/500 g soil, 250 μm – 1 mm: 180–200 particles/500 g soil	Microplastics might not be a carrier of pesticides to earthworms.	Rodriguez-Seijo et al. (2018a)
		250–1000 μm	62.5, 125, 250, 500 and 1000 mg/kg soil dry weight	Resulted oxidative stress and caused energy metabolism changes.	Rodriguez-Seijo et al. (2018b)
		< 100 μm (17.69 %), 100–200 μm (74.38 %), 200–400 μm (7.43 %)	0.1, 0.25, 0.5, 1.0, 1.5 g/kg soil dry weight	Increased catalase activity and malondialdehyde content, and stimulated acetylcholine esterase.	Chen et al. (2020)
Earthworm; chicken (*Gallus gallus domesticus*)	LDPE	< 5 mm	/	Microplastics might enter terrestrial food webs.	Huerta Lwanga et al. (2017b)
Earthworm (*Aporrectodea rosea*)	HDPE	102.6 μm	1 g/kg dry soil	Reduced biomass.	Boots et al. (2019)

Note. PE, polyethylene; LDPE, low-density polyethylene; HDPE, high-density polyethylene.

microbes of the insects, suggest that soil-dwelling animals might facilitate the polyethylene degradation.

Microorganisms can colonize microplastics, through which microplastics provide a habitat for them to form distinct microbial communities from the surrounding soil environment (Miao et al., 2019; Qiang et al., 2021). This colonization process has important implications for biodegradation of polyethylene microplastics. It is hypothesized that the first step of biodegradation of polyethylene is the establishment of polyethylene-degrading microorganisms on the surface of polyethylene microplastics (Ammala et al., 2011; Hou et al., 2022; Jeon et al., 2021; Zadjelovic et al., 2022), and then the microorganisms can secrete extracellular oxidase, for instance, laccase and esterase, to oxidize, dehydrogenate and break the carbon-carbon bond of the polyethylene molecular chains for enzymatic depolymerization of the polyethylene microplastics into molecular fragments with a production of oxidative products, e.g., acetic acid (Ammala et al., 2011; Hou et al., 2022; Jeon et al., 2021; Koutny et al., 2006; Wilkes and Aristilde, 2017; Zadjelovic et al., 2022). Oxidases are essential for enzymatic polyethylene cleavage wherein C—C and C—H bonds are oxidized into carboxylic or hydro-carboxylic acids, esters, as well as aldehydes and alcohols (Ammala et al., 2011; Zadjelovic et al., 2022). Consequently, the polyethylene-degrading microorganisms take up and consume oxidation products for energy production and biomass formation with CO_2 release through the tricarboxylic acid cycle, achieving polyethylene biodegradation (Li et al., 2019; Wilkes and Aristilde, 2017; Zadjelovic et al., 2022) (Fig. 1 and 2). Also, the microorganisms could secrete extracellular hydrolases for breaking ester bonds through a nucleophilic attack on carbonyl carbon atoms created by previous oxidation reactions (Devi et al., 2016; Wilkes and Aristilde, 2017).

The PE molecule only contains non-polar C—C and C—H bonds which do not provide centers for nucleophilic or electrophilic attack, and PE molecules are aligned densely in the formation of semicrystalline structures and are highly hydrophobic; as a result, PE could only provide a limited number of free chain ends for enzymatic action in its surface (Ammala et al., 2011; Koutny et al., 2006). Therefore, PE biodegradation is hard to interpret. While there are some reported studies that used pure cultures to obtain signs of PE biodegradation with loss of PE weight and bacteria and fungi growing on films, the results suggested that the

Table 4
Effects of polyethylene microplastics on soil properties in agroecosystem.

Polymers	Size	Exposure dose	Effects	Refs.
PE	710–850 μm, 1180–1400 μm, 1700–2000 μm, 2360–2800 μm	750 mg (2625, 424, 203 and 75 particles for different size) per 2.5 kg of soil plus 5.0 g of dry leaf litter	Facilitate transport of microplastics into soils, through casts, burrows, egestion and adherence to the earthworm exterior.	Rillig et al. (2017)
LDPE	< 50 μm (50 %), 50–100 μm (27 %), 100–150 μm (23 %)	1 %, 3 %, 7 % (w/w) litter dry weight	Facilitated the transport of glyphosate from ground to deeper soil layers.	Yang et al. (2019)
LDPE	5 mm, 250 μm – 1 mm	5 mm: 8 particles/500 g soil; 250 μm-1 mm: 180–200 particles/500 g soil	Enhanced input of pesticide chlorpyrifos to soil.	(Rodríguez-Seijo et al. (2018a)
LDPE	50 μm – 1 mm	1 % (w/w) soil dry weight	Increased C:N ratio of the soil.	Qi et al. (2020b)
LDPE	678 μm	1 % and 5 % (w/w) soil dry weight	Inhibited fluorescein diacetate hydrolase activity and stimulated urease and acid phosphatase activities of soil	Fei et al. (2020)
HDPE	102.6 μm	1 g/kg dry soil	Altered size distribution of water-stable soil aggregates (meaning soil stability) and decreased soil pH.	Boots et al. (2019)

Note. PE, polyethylene; LDPE, low-density polyethylene; HDPE, high-density polyethylene.

biodegradation rate is extremely low as it would take weeks to months to biodegrade a little amount of PE mass (Table 2). It is crucial to identify and isolate more efficient PE-degrading microorganisms from nature environments.

5. Microbial colonization of polyethylene microplastic and its influence on soil microbial community

The polyethylene microplastics are usually a form of transparent film pieces, having lower density and hardness, and presenting softer texture for colonizing microorganisms as compared with natural materials or other types of microplastics (Miao et al., 2019; Qiang et al., 2021). This can promote the formation of distinct microbial communities on the microplastic surface from the surrounding environments. Microorganisms play a crucial role in mediating soil enzyme activities and nutrient element circulation by degrading organic matter, especially in the plant rhizosphere (Fei et al., 2020; Qi et al., 2020b) (Fig. 2 and 3). The selective colonization of microplastics by soil microorganisms can cause changes in soil microbial community composition, e.g., increased abundance of bacteria associated with nitrogen fixation and decreased abundance of bacteria related to xenobiotics biodegradation (Fei et al., 2020). And the selective microorganism distribution can elicit changes in enzyme activities, e.g., inhibited fluorescein diacetate hydrolase activity and stimulated urease and acid phosphatase activities of soil (Fei et al., 2020), and cause changes in nutrient elements content, e.g. increased C: N ratio of the soil (Qi et al., 2020b). It has been demonstrated that LDPE microplastics can significantly impact rhizosphere bacterial community structure (Qi et al., 2020b). HDPE microplastics could elicit significant changes in soil microbial activities (de Souza Machado et al., 2019). LDPE microplastics could promote the abundance of bacterial families *Burkholderiaceae* associated with nitrogen fixation and decline the abundance of *Sphingomonadaceae* and *Xanthobacteraceae* related to the biodegradation of xenobiotics in the soil (Fei et al., 2020).

6. Accumulation of polyethylene microplastics in organisms: indoor and field studies

The biological uptake of polyethylene microplastics in organisms has been demonstrated in many indoor experiments. For example, PE microplastics could be ingested by springtails (*Folsomia candida*) with an edible size of less than 66 μm (Kim and An, 2020). HDPE microplastics (Hodson et al., 2017) can be accumulated in earthworms (*Lumbricus terrestris*), and LDPE microplastics can be ingested by earthworms (*Eisenia fetida*) (Chen et al., 2020; Wang et al., 2019) and in a dose-response manner (Chen et al., 2020). Furthermore, the status quo shows that polyethylene microplastics in soil could adhere to the surfaces of Lemna minor (L.) (Mateos-Cárdenas et al., 2019), and polystyrene and polymethylmethacrylate microplastic particles can penetrate the stele of wheat and lettuce at sites of lateral root emergence based on the crack-entry mode and be transported from the roots to the shoots forced by the transpirational pull (Li et al., 2020). So there is a chance that microplastics might enter human food chain through plants. However, the information about the transportation of polyethylene microplastics in crops is limited.

Polyethylene microplastics have also been detected in organisms in farmland fields. In one example, PE microplastics were detected at the concentration of ~ 2 particles/individual in earthworms (Zhang et al., 2020a) and ~ 2 particles/individual in crayfishes, eels, and loaches (Lv et al., 2019) in the agricultural field. In another field study, LDPE microplastics were detected in soil, earthworm casts, and chicken feces, and the concentrations were increased from the soil, to earthworm casts, and to chicken feces, indicating that microplastic may enter terrestrial food webs (Huerta Lwanga et al., 2017b).

7. Impacts of polyethylene microplastics on soil-dwelling animals

Polyethylene microplastics have various impacts on soil-dwelling animals (Table 3). PE microplastics can be easily transported into soils by earthworms through casts, burrows, egestion, and adherence to the earthworm exterior (Rillig et al., 2017), causing histopathological damage and immune system responses of earthworms (Rodriguez-Seijo et al., 2017). In addition, they can also decrease the mobility (velocity and distance) of springtails (Kim and An, 2019; Kim and An, 2020), increase avoidance rate, suppress reproduction of springtails, decrease bacterial diversity in springtail gut (Ju et al., 2019), reduce body length and intestinal calcium level, increase intestinal glutathione S-transferase 4 enzyme expression, and induce reproduction inhibition of nematode (Lei et al., 2018). Furthermore, HDPE can reduce the biomass of earthworms (Boots et al., 2019), and LDPE microplastics can cause oxidative stress and energy metabolism changes in earthworms (Rodriguez-Seijo et al., 2018b), and increase catalase activity and malondialdehyde content, and stimulate acetylcholine esterase of earthworms (Chen et al., 2020), as well as influence earthworm gallery (all burrows per box) volume (Yang et al., 2019).

As polyethylene microplastics are ingested by soil-dwelling animal, the opportunity of gaining energy from food might be decreased as microplastics are not digested but occupying the space. Investment in the energy supplement of the soil-dwelling animal seems to be compromised under microplastic pressure (Aira et al., 2007; Huerta Lwanga et al., 2016; Sussarellu et al., 2016). It interferes with energy reserves and finally causes an imbalance of energy distribution in the animals. The imbalance of energy investment could subsequently induce changes in the structure of the intestinal microbial community, cause oxidative stress, and even provoke changes in feeding behavior, locomotion velocity and distance, avoidance, and other behaviors of the soil-dwelling animals (Huerta Lwanga et al., 2016; Ju et al., 2019; Kim

Table 5
Impacts of polyethylene microplastics on soil microorganisms and crop plants in agroecosystem.

Polymers	Size	Exposure dose	Organisms	Test species	Impacts	Refs.
LDPE	678 μm	1 % and 5 % (w/w) soil dry weight	Soil bacteria	Soil bacteria	Caused changes in abundance of bacterial families associated with nitrogen fixation and biodegradation of xenobiotics in the soil.	Fei et al. (2020)
LDPE	50 μm-1 mm	1 % (w/w) soil dry weight		Rhizosphere bacteria	Changed the structure of the rhizosphere bacterial community.	Qi et al. (2020b)
HDPE	643 μm	2.0 % (w/w) soil fresh weight		Soil bacteria	Caused changes in soil microbial activities.	de Souza Machado et al. (2019)
LDPE	500 μm – 1 mm (12.5 %), 250–500 μm (62.5 %), 50–250 μm (25 %)	1 % (w/w) soil dry weight	Crop plants	Wheat (*Triticum aestivum*)	Affected growth of wheat plant.	Qi et al. (2018)
LLDPE	50 nm	10, 100, 500, 1000 mg/L		Wheat (*Triticum aestivum L.; Xiaoyan 22*)	Affected wheat seed germination and inhibited wheat bud length.	Lian et al. (2019)
HDPE	150 μm, 1000 μm, 4000 μm	0.1, 0.5, 1 g/kg soil dry weight		Wheat *(Triticum aestivum L.; Bainong 4199)*	Reduced germination level of wheat seeds.	Zhang et al. (2021)
HDPE	643 μm	2.0 % (w/w) soil fresh weight		Spring onion (*Allium fistulosum*)	Caused changes in plant biomass, tissue elemental composition, root traits.	de Souza Machado et al. (2019)
HDPE	0.023–0.038 mm, 0.55–0.88 mm, 0.106–0.15 mm	0.1, 1, 10, 100 mg/g silica sand		Mung bean *(Vigna radiata)*	Decreased root length, bud length, fresh weight, and moisture content of the seedling.	Liu et al. (2019)

Note. LDPE, low-density polyethylene; HDPE, high-density polyethylene; LLDPE, linear low-density polyethylene.

and An, 2020). On the other hand, the soil-dwelling animal could create a bio-pore (holes in the soil formed when soil-dwelling animals crawl through the soil) in the soil to avoid becoming trapped, and it has been demonstrated that the locomotion of the soil-dwelling animal is related to the behavior of microplastics in the bio-pore. Microplastics can move into bio-pores within seconds, causing an influx which in turn can immobilize the movement of the soil-dwelling animal (Kim and An, 2019; Huerta Lwanga et al., 2017a). The behavior performance of the soil-dwelling animals is crucial for the formation of soil structure. The effects of microplastics on soil-dwelling animals might consequently have a significant effect on soil structure.

8. How polyethylene microplastics affect soil properties

Polyethylene is highly hydrophobic, showing non-polar properties as a result of long-chain polymer saturated with ethylene bonds (Wilkes and Aristilde, 2017). It has been reported that one type of hydrophobic microplastic, polyethylene terephthalate, can induce soil water repellency and limit capillary flow (Cramer et al., 2022). And HDPE microplastics might contribute to the change of soil pore space and soil aggregation (de Souza Machado et al., 2019). The occurrence and distribution of polyethylene microplastics among soil particles might contribute to soil water repellency and influence wetting, runoff, water availability, as well as evapotranspiration of soil (Smettem et al., 2021). As a result, those could consequently disrupt soil properties, for instance, pH, bulk density, and cycling of nutrient elements, ultimately disturbing the availability of water and nutrients for plants (Boots et al., 2019; de Souza Machado et al., 2019; Smettem et al., 2021; Qi et al., 2020a).

Many studies have examined the impacts of polyethylene microplastics on soil systems (Table 4). LDPE microplastics can promote the input of pesticides into the soil (Rodriguez-Seijo et al., 2018a). LDPE can significantly increase C:N ratio of the soil (Qi et al., 2020b). HDPE can alter the distribution of water-stable soil aggregates of different sizes, and HDPE could decrease soil pH (Boots et al., 2019). LDPE can significantly change soil porosity, bulk density, field capacity, water repellency, and saturated hydraulic conductivity, while they had no effect on soil electrical conductivity, pH, and aggregate stability (Qi et al., 2020a). PE microplastics in soil can decrease the sorption capacity of the soil, instigate the mobility of organic contaminants (Hüffer et al., 2019), and cause soil hardening (Zhao et al., 2022), so that increasing fertilizer inputs and then enhance agricultural cost (Jiang et al., 2012). In addition, LDPE microplastics could inhibit fluorescein diacetate hydrolase activity and stimulate urease and acid phosphatase activities in the soil (Fei et al., 2020).

9. How polyethylene microplastics affect crops

Polyethylene microplastics have been shown to cause impacts on crop plant growth (Table 5). LDPE microplastic can affect wheat plant growth during vegetation and reproduction growth stages (Qi et al., 2018). de Souza Machado et al. (2019) reported that HDPE microplastics could elicit significant changes in spring onion biomass, tissue elemental composition, and root traits. LLDPE microplastics can inhibit wheat seed germination and wheat bud length at a low concentration while promoting germination at a high concentration (Lian et al., 2019). HDPE microplastics could suppress the germination of wheat seeds (Zhang et al., 2021). In addition, another study showed that although HDPE microplastics had no effect on the germination rate of mung bean seeds, they could significantly reduce the root length, bud length, fresh weight, and moisture content of the seedlings (Liu et al., 2019).

The effects of polyethylene microplastics on soil properties and soil organisms could eventually contribute to their influence on plant growth since the growth and development of plants rely on soil physicochemical conditions, which in turn depend on the behavior of soil-dwelling animals, and nutrient element circulation mediated by the soil microorganisms (Fig. 3). In addition, microplastics in the soil can attach to the surface of seeds and seedling roots of plants, which might inhibit water absorption and respiration of the seed and seedling, and consequently influence the development of the seed and bud (Lian et al., 2019; Liu et al., 2019; Zhang et al., 2021). Furthermore, microplastics can be taken up by the plant via roots and be transported from the roots to the shoots (Li et al., 2020), which might pose potential effects on plant development. Most importantly and interestingly, the occurrence of microplastics in the plant rhizosphere soil can contribute to the selection of rhizosphere microbiome distribution (de Souza Machado et al., 2019; Fei et al., 2020; Qi et al., 2020b), it would cause changes of nutrients cycling and the enzyme activities of soil, and eventually influence plant root traits and plant biomass (Fig. 3).

The effects of polyethylene microplastics in agroecosystems are manifested in their effects on soil properties, soil-dwelling animal performance, and community structure of soil microorganisms.

Microplastics in soil can further directly or indirectly influence crop plant growth and development. The size of microplastics is crucial to their impacts, as it determines the opportunity and ways of interactions between microplastics and soil particles. Smaller microplastics are likely to interact with soil particles and can be ingested by and accumulate in soil-dwelling animals. With regard to the frequent occurrence and the impacts of polyethylene microplastics, comprehensive treatment measures for mulch film contamination should be considered promptly, and attention needs to be paid to related control and remediation methods, for instance, the development of efficient recycling technologies for plastic mulch films (Huang et al., 2020).

10. Conclusions and future directions

This work systematically summarized the distribution, aging process, and biological impacts of polyethylene microplastics in agroecosystems, as well as potential mechanisms of how polyethylene microplastics affect soil properties, soil biota, and crop plants. Currently, the occurrence of polyethylene microplastics in the soil environment has caused concern. However, the following issues deserve further attention from researchers and are expected to be addressed in future works:

- Polyethylene microplastics are ubiquitous in soil, water, and organisms in agroecosystems, and plastic mulch is considered as the main source. With the increasing polyethylene mulch use, the accumulation of polyethylene microplastics will increase. Improving the recycling efficiency of plastic mulch may be an effective way to avoid the residue of plastic mulch debris and polyethylene microplastics in the soil. This needs to be appropriately taken into account by agricultural departments when formulating policies for mulch film use.
- The transportation and distribution of polyethylene microplastics in crop plant organs, especially in the edible parts, e.g., fruit, need to be investigated. The occurrence of polyethylene microplastics in crops may lead to human ingestion of polyethylene microplastics through the food chain. However, the information about the uptake and transportation pathway of polyethylene microplastics in crops is limited.
- The impacts of polyethylene microplastics on crop plants should be investigated comprehensively since crop growth is vital for agricultural production and an endpoint of the effects of polyethylene microplastics in agroecosystems. A few studies have demonstrated that polyethylene microplastics can cause impacts on crop plants. However, the information on the impacts of polyethylene microplastics on crop plants is still limited, and the mechanisms have not been well revealed.
- A criterion should be established for measuring the level of soil polyethylene microplastic pollution. Though many studies have detected the distribution and concentration of polyethylene microplastics in agroecosystems, there are no reports on which concentrations meet pollution standards or thresholds. This makes it difficult to determine if the concentration of polyethylene microplastics causes environmental risk. Furthermore, based on this context, the degree of microplastic pollution in the areas where polyethylene microplastics are found could not be evaluated, and the specific policy for mulch film use is difficult to be formulated. More studies on the effects and mechanisms of polyethylene microplastics need to be conducted to establish relevant criteria.
- It is important to identify, isolate and apply efficient polyethylene-degrading microorganisms using cutting-edge techniques from and in nature environments, and the microbial-driven biological degradation process would be considered as the important microbial synergy.

Declaration of Competing Interest

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

Data Availability

No data was used for the research described in the article.

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