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REVIEW

Impact of microplastics on soil (physical and chemical) properties, soil biological properties/soil biota, and response of plants to it: a review

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Abstract

Microplastics (MPs) have emerged as a widespread environmental contaminant, raising growing concerns about their impact on terrestrial ecosystems. This comprehensive review paper highlights the effects of MPs on soil properties, soil organisms, and plants, shedding light on the complex interactions within these critical components of terrestrial environments. In terms of soil properties, plastics, ranging from macroplastics to mesoplastics, microplastics, and nanoplastics, have been found to exert significant influence. They can alter soil physical attributes, including texture, structure, bulk density, water aggregate stability, water holding capacity, and rainwater infiltration. Microplastics can affect soil chemical properties by influencing pH levels, electrical conductivity, nutrient cycling, and enzyme activity, and even can cause heavy metal accumulation in plants. These alterations in soil properties have far-reaching implications for ecosystem health and agricultural productivity. Furthermore, microplastics have substantial repercussions on soil organisms, particularly earthworms, collembolans, and microbial communities comprising bacteria and fungi. These organisms play pivotal roles in nutrient cycling and soil health. Microplastics can disrupt their habitats, affect their behavior, and potentially lead to changes in soil biota composition, with widespread effects throughout the terrestrial food web. Microplastics influence plant growth and development; even the microplastic can be uptaken and translocated within plant tissues. Food safety and ecosystem dynamics are affected by these effects. This review paper emphasizes the urgency of understanding the complex interactions between microplastics and terrestrial ecosystems. It highlights the need for further research to comprehensively assess the extent and implications of microplastic contamination in various soil types, under different environmental conditions, and concerning diverse plastic characteristics. Standardized methodologies for studying these interactions are essential to facilitate comparisons across studies.

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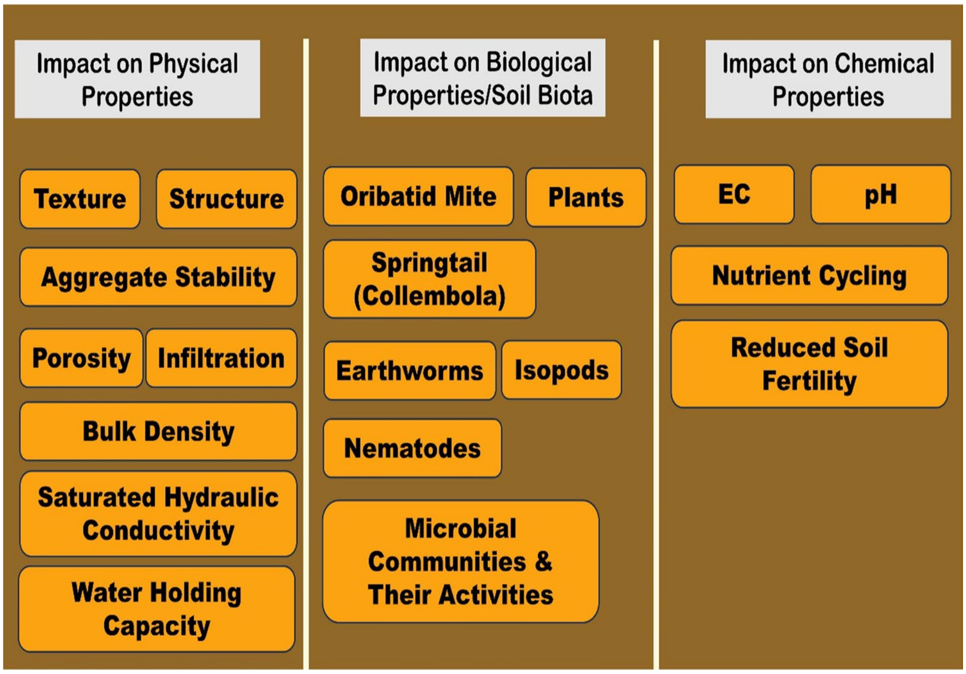
Graphical abstract



Keywords Effect of MPs on soil · Microplastics and soil properties · Effect on plants · Effect on soil organisms · Microplastics and soil physical properties · Microplastics and chemical properties · Microplastics · Nanoplastics · Abundance

Introduction

In a world where plastic has become an inseparable part of our lives because of its convenience, low cost, high durability, waterproofing, good elasticity, and hygiene (Kim et al. 2020b; Wang et al. 2022a; Li et al. 2022b; Xiang et al. 2022), its impact stretches far beyond what meets the eye penetrating even the very ground beneath us. Because of the many benefits associated with plastics, they are used in various industries like buildings, packaging, household goods, electronics and electrical appliances, auto parts, and agricultural goods (Kim et al. 2020b; Xiang et al. 2022). Now, a world without plastics is unimaginable. The first synthetic product was Bakelite, introduced in the early twentieth century. Besides the military, plastic use was not widespread until World War II (Geyer et al. 2017).

In the packaging industry, plastic use is increasing day by day as the world shifted from reusable plastics to disposable plastics, which are ultimately ending up in municipal solid waste; as a result, municipal solid waste (by mass) increased from less than 1% in 1960 to 10% in 2005 in the middle & high-income countries (Geyer et al. 2017). In 1950, plastic production was 2 million tonnes (Mt), and in 2018, it was 359 Mt, which showed a growth of 8.4% annually (Kim et al. 2020b). Reportedly, till 2019, there was 368 Mt of plastic and plastic products production globally (Li et al. 2022b), and only China produced 114 Mt and 59 Mt by Europe, that's going to increase by two folds by 2040 (Sharma et al. 2023).

(Geyer et al. 2017) reported that 8300 Mt had been produced till the time of his report. And 6300 Mt of plastic waste had been made from 1950 till 2015; around 12% has been incinerated, 9% has been recycled, and 79% (4900 Mt) ended up in landfills or the natural environment. If the current rate continues, 12,000 Mt of plastic waste will end up in landfills or the natural environment (Geyer et al. 2017). Many researchers think that soil is a giant sink or dump yard or plastic waste compared to oceans due to the more significant release of plastics into the terrestrial environment (de Souza Machado et al. 2018; Rochman 2018; Helmberger et al. 2020; Kim et al. 2020b). According to an estimate, 4–23 folds of more plastics are added to terrestrial ecosystem compared to aquatic (Li et al. 2022b). Only 1% of global plastic waste is added to the oceans; the rest is deposited in the soils and freshwater (Zhang and Liu

2018). According to (Wang et al. 2022a), 90% of plastic waste enters the soil ecosystem directly and indirectly.

Plastics are further classified based on their size: macroplastics (> 25 mm), mesoplastics (5–25 mm), microplastics (1–5 mm), and nanoplastics (1–100 nm) (Sharma et al. 2023). Some researchers further classify microplastics as large microplastics (1–5 mm) and small microplastics (1 µm—1 mm) (Kim et al. 2020b). Some researchers also classify microplastics as primary microplastics (tiny in size and used in cosmetics, clothing, fish nets, shampoo, and medical purposes) and secondary microplastics (produced by the fragmentation/degradation of microplastics) (Zhang and Liu 2018; Li et al. 2022b; Sharma et al. 2023). Primarily, scientists define microplastics generally as under 5 mm (Ryan et al. 2009; Law and Thompson 2014; Rillig 2018; Rillig et al. 2018; Rochman 2018; Helmberger et al. 2020). In this paper, we will only discuss the microplastics.

In the ocean, microplastics were reported in the early 1970s (Carpenter and Smith Jr. 1972; Colton Jr. et al. 1974; Helmberger et al. 2020). And (Rillig 2012) discussed microplastics in the soil for the first time about a decade ago (Helmberger et al. 2020). Microplastic pollution in soils is increasing day by day; in extensively polluted top soils, reports have indicated microplastic concentrations reaching as much as 7% of the total weight (de Souza Machado et al. 2018). Similarly, Australian industrial soils 300 mg kg^{-1} to over 67,000 mg kg^{-1} (around 6.7% microplastic per total soil weight) (Rillig 2018). The abundance of microplastics at different locations in the world can be seen in Table 1. Annually, "63,000–430,000 and 44,000–300,000 tonnes of microplastics could being added in the soils of farmlands of Europe and North America", respectively (Nizzetto et al. 2016b, a).

Microplastics can disturb soil ecology, be taken up by plants, disturb nutrient cycling, reduce soil quality/health, and enter the food chain. Microplastics can act as persistent pollutants, stay in the soil for long because of their anti-degradation property/behavior, and adversely affect soil properties. Microplastics might also absorb detrimental contaminants from the soil solution and subsequently concentrate them in the soil (Rillig 2012; Zhang and Liu 2018; Iqbal et al. 2020; Qi et al. 2020; Elbasiouny et al. 2022; Zhang et al. 2022a). In this paper, we will study the impact of MPs on soil properties (physical, chemical, and biological/ biota) and the response of plants to them.

Sources and transport of microplastics towards soils

Microplastics can be added to the soil intentionally and unintentionally. While using plastic film mulch and plastic in fertilizers, we are adding microplastics intentionally. The example of unintentional deposition of microplastics can occur in soil when using sewage sludge, compost, fermented organic wastes, and irrigation with the water from the contaminated water bodies (de Souza Machado et al. 2018; Iqbal et al. 2020; Elbasiouny et al. 2022; Joos and De Tender 2022; Zhang et al. 2022a). And atmospheric deposition (like tire abrasion, deposition of industrial and consumer plastic waste, etc.) of microplastics is also reported even in very remote places, even at high mountains (Scheurer and Bigalke 2018; Cao et al. 2021; Yu et al. 2021c; Joos and De Tender 2022; Li et al. 2022b). Flooding can also cause the deposition of MPs in the soil (Scheurer and Bigalke 2018).

Using sewage sludge as an irrigation source adds more microplastics into the soil compared to oceans annually (Scheurer and Bigalke 2018). According to an estimate, 125 to 850 tons of microplastics per million inhabitant are being added to the European agricultural soils (Nizzetto et al. 2016a). Reportedly, up to 4,196 to 15,385 microplastic particles can be in the per kilogram of the sludge (Mahon et al. 2017; Li et al. 2022b). According to an estimate, 50% of the sewage sludge is being used as fertilizers in developed countries in Europe and North America (Nizzetto et al. 2016a; Sharma et al. 2023), and sewage sludge is also being used as a fertilizer and irrigation source in developing countries like Pakistan (Azam et al. 1999; Keskin et al. 2009). In China, 0.156 Mt MPs are transported to the environment by the sludge (Li et al. 2018b).

Untreated wastewater contains microplastics at a very high rate from washing clothes using detergents and effluents from personal care products. Using this type of wastewater for irrigation purposes can add microplastics to the soil (Li et al. 2022b). Over 90% of MPs are captured in sewage sludge during wastewater treatment. The efficiency of capturing these MPs relies on their particle size and density. Both primary and secondary treatment phases of sewage treatment primarily trap microplastics that have a higher density than water.

Further refinement occurs in tertiary filtration, where larger buoyant particles are successfully eliminated. As anticipated, microplastic particles that are smaller and lighter are discharged with the treated wastewater. In other words, sewage sludge treatment plants could be more efficient in eliminating MPs (Nizzetto et al. 2016a; Yu et al. 2021c).

Even compost can contain up to 14–895 microplastic particles kg^{-1} (Li et al. 2022b). In the U.S., synthetic fibers were found in the soils where organic waste material was applied (Zubris and Richards 2005). Particle counts ranging from 14 to 895 per kilogram of dry weight were observed (using a conservative estimate where 1 kg of compost comprises around 50% dry weight content) for microplastic particles larger than 1 mm (Weithmann et al. 2018).

Table 1 Abundance of microplastics in soil globally

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
Germany	Franconia	Agricultural Land	PE	1–5 mm	0.7143 ± 0.7263 particles/kg		(Piehl et al. 2018)
			PS		0.2857 ± 0.8254 particles/kg		
			PP		0.1429 ± 0.3631 particles/kg		
	Schleswig–Holstein	winter rapeseed—winter wheat—winter barley	PE, PP, PA, others	1–5 mm	0–217.8 particles/kg	WI, OF	(Harms et al. 2021)
	Hesse	Floodplain Areas	LDPE	2–5 mm	1.88 particles/kg		(Weber and Opp 2020)
	Central Germany	Agricultural soil		< 5 mm	0.00–56.18 particles/kg		(Weber et al. 2022)
Canada	Ontario	Agricultural Land	PS, PE, PP, PES, Arc, PU, PA, PMMA, others	< 5 mm	18 – 298 particles/kg	SA	(Crossman et al. 2020)
Korea	Yeoju	Traffic soil	PE, PP, PS, PVC, SBR	< 5 mm	1108 particles/kg	MF, CT, AD	(Choi et al. 2020)
		Agricultural soil			664 particles/kg		
		Residential soil			500 particles/kg		
		Forest soil			160 particles/kg		
	Yong-In	Agricultural Land	PE, PP, PET	0.1–5 mm	10–7,630 particles/kg	MF, LI	(Kim et al. 2021)
Switzerland	Berne	Floodplain Soils	PE	0.1–5 mm	0–593 particles/kg		(Scheurer and Bigalke 2018)
USA	Washington	Wetland Park and Aquatic Gardens	PE	75 µm – 5 mm	334–3068 particles/kg		(Helcoski et al. 2020)
	Pucnachen, Mexico	Home garden	PE, fiber, PS	< 5 mm	0.87 ± 1.9 particles/g		(Huerta Lwanga et al. 2017b)
	Mellipilla, Chile	Corn land		< 5 mm	600–10,400 particles/kg	SA	(Corradini et al. 2019)
China	Hangzhou	Coastal Plain	PE	50 µm–5 mm	~ 60 particles/kg		(Zhou et al. 2020a)
	Shihezi	Agricultural Land/Cotton Field	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	MF	(Huang et al. 2020)
		Green-belt soil	PS, PE	20 µm–5 mm	287–3227 particles/kg		(Liu et al. 2022)

Table 1 (continued)

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
	Alar	Agricultural Land	PE	31 µm–4.9 mm	161.50 ± 5.20 particles/100 g		(Hu et al. 2021)
				1.1 µm–1.88 mm	11.20 ± 1.10 particles/100 g		
	Shanxi	Agricultural Land	PS, PVC, PE, PET, PP, HDPE	0–0.49 mm	1,430 – 3,410 particles/kg	SA, WI, MF	(Ding et al. 2020)
	Hebei, Shandong, Hubei, Shaanxi, Jilin	Wheat Land	PA, PP, PVC, PS, PE, Acr, polyester	< 5 mm	3910 ± 1031 particles/kg	SA, WI, MF	(Wang et al. 2021)
		Paddy Land		< 1 mm	5490 ± 573 particles/kg		
		Wood Land		0.02 and 0.2 mm	3683 ± 362 particles/kg		
		Orchard Land		< 1 mm	3386 ± 593 particles/kg		
		Mulch Film Soil		< 1 mm	5386 ± 835 particles/kg		
		Greenhouse Soil		< 1 mm	5124 ± 632 particles/kg		
	Qinghai	Agricultural Land		0.45 µm–5 mm	240–3660 particles/kg		(Lang et al. 2022)
	Qinghai–Tibet Plateau	Farmland, Mulching Land Greenhouse Land	PP, PE, PS, PA, and others	< 0.5 mm	53.2 ± 29.7 particles/kg (0–3 cm depth) 43.9 ± 22.3 particles/kg (3–6 cm depth)	MF, WI, LI	(Feng et al. 2021)
	Tibetan Plateau	Primary soil	PVC, PE, PP, PS	< 5 mm	47.12 particles/kg		(Yang et al. 2022)
	Wuhan	Vegetable land	PA, PP, PS, PE, PVC	< 0.2 mm	320–12,560	SA, MF	(Chen et al. 2020b)
		Vegetable land	PE, PA, PP, PS, PVC, and others	0.01–0.1 mm	4.3×10^4–6.2×10^5 particles/kg	SA, WI, MF, LI	(Zhou et al. 2019)
	Enshi	Tobacco field		≤ 1.0 mm	646.67–2840 particles/kg	MF, SA, OF	(Zhang et al. 2022b)
	Guilin	Citrus orchard soil	PP, PE, PET	< 5 mm	545.9 particles/kg with 30t/ha of sludge compost		(Zhang et al. 2020b)
					87.6 particles/kg with 15/ha of sludge compost		
					5.0 particles/kg without compost		
	Dian Lake (Southwestern China)	Agricultural soil		0.03–10 mm	7100–42,960 particles/kg		(Zhang and Liu 2018)

Table 1 (continued)

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
	Hangzhou Bay	Vegetable land	PE, PP, PA, PES, Acr, nylon, and others	0.06–5 mm	571 particles/kg (mulching)	SA, WI, MF, LI	(Zhou et al. 2020a)
				1–3 mm	263 particles/kg (non-mulching)		
	Daliao River Basin	Loam soil	PP, PE	5 µm–5 mm	60–980 particles/kg		(Lihua et al. 2020)
	Harbin	Vegetable and corn land	PE	0.05–5 mm	50 ± 87—400 ± 692 particles/kg	MF	(Zhang et al. 2020c)
	Shouguang	Vegetable land	PP, EPC, PE, PS, PES, PU, ABS, PMMA, and others	< 0.5 mm	275–5411 particles/kg (0–5 cm depth)	MF, LI, OF, RO	(Yu et al. 2021b)
					179–7175 particles/kg (5–10 cm depth)		
					307 – 4507 particles/kg (10–25 cm depth)		
	Shenyang	Agricultural soil	PE	< 5 mm	3,700,000 particles/kg (fertilized plot)		(Li et al. 2022a)
					2,200,000 particles/kg (non-fertilized plots)		
					8,885 particles/kg (topsoil)		
					2,899 particles/kg (deep subsoil)		
	Shandong	Coastal soils	PE, PP, PS, PUR	< 5 mm	1.3 to 14,712.5 particles/kg		(Zhou et al. 2018)
		Agricultural soil	PP, PE	< 5 mm	1444 ± 986 particles/kg		(Yu et al. 2021b)
	Jiangsu	Agricultural soil	PE, PP, PET, PAN, CL	1 – 5 mm	420 – 1290 particles/kg	SA	(Li et al. 2019b)
	Tangshan	Tidal soil		0.12 to 4.67 mm	634 particles/kg		(Qian et al. 2016)
	North-western- Loess plateau China	Agricultural soil,	PE, PP	< 5 mm	40 – 100 particles/kg		(Zhang et al. 2018)
		Orchard soil			120 – 320 particles/kg		
		Greenhouse soil			80 – 100 particles/kg		
	Guangxi	Coastal mangrove sediment	PP, PS	50 µm – 5 mm	875.3 particles/kg		(Zhou et al. 2020b)
	Fujian	Coastal mangrove sediment	PP, PS	50 µm – 5 mm	198.4 particles/kg		(Zhou et al. 2020b)
	Hainan	Coastal mangrove sediment	PP, PS	50 µm – 5 mm	146.0 particles/kg		(Zhou et al. 2020b)

Table 1 (continued)

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
	Zhejiang	Coastal mangrove sediment	PP, PS	50 µm – 5 mm	116.7 particles/kg		(Zhou et al. 2020b)
	Shanghai	Farmland soil	PP, PE, PET	0.02 to 5 mm	78.00 ± 12.91 particles/kg (shallow soil)		(Liu et al. 2018)
					62.50 ± 12.97 particles/kg (deep soil)		
		Soil from Rice-Fish co-culture ecosystem	PE, PP, PVC	< 5 mm	10.3 ± 2.2 particles/kg		(Lv et al. 2019)
	Tianjin		PP, PS	0.1 to 3.2 mm	75 to 95 particles/kg		(Han et al. 2019)
	Yunnan-Guizhou Plateau	Agricultural Soil		< 5 mm	900 to 40,800 particles/kg		(Huang et al. 2021)
	Mu Us Sand Land (comprised of Yulin city in Shaanxi province, ordos city in the Inner Mongolia Autonomous Region, and Yanchi County in Ningxia Hui Autonomous Region.)	Sandy soil	PP, PE, PS	< 5 mm	2696.5 particles/kg		(Ding et al. 2021)
	Guizhou	Agricultural Soil		5 µm – 5 mm	3000 – 8640 particles/kg		(Zhang et al. 2022c)
	Baoding	Urban–Rural Soil	PP	0 to 35 µm	23.3%		(Du et al. 2020)
			PVC		16.3%		
			PET, and polyamide (PA6)		30.2%		
	Yangtze Plain	Riparian soil	PE, PP	0.45 µm-5 mm	3877 ± 2356 particles/m^2		(Zhou et al. 2021b)
		Agricultural soil	PP	< 5 mm	4.94 – 252.7 particles/kg		(Cao et al. 2021)
	Jiangxi	Agricultural soil	PP, PES, PE	< 5 mm	16.4 ± 2.7 particles/kg		(Yang et al. 2021a)
	Taiwan	Cabbage, corn, asparagus, pumpkin, guava	LDPE, PE, Oxidized PE, PS, PP	1 – 3 mm (65%), 3 – 5 mm (12%), 5 mm (8%)	2 – 117 particles/m^2		(Fakour et al. 2021)
	Xinjiang	Vegetable farm and orchard	PE	0.9 – 2.0 mm	10.10 – 61.05 mg/kg		(Li et al. 2020b)
		Plastic film mulched soil		10 µm – 5 mm	2.13E + 04 ± 7200 particles/kg		(Jia et al. 2022)

Table 1 (continued)

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
	Inner Mongolia	Agricultural soil		0.45 µm – 5 mm	2526–6070 particles/kg		(Wang et al. 2020d)
	28 WWTPs located in 11 China provinces	Wastewater treatment plants (WWTPs)	Polyolefin, acrylic fibers, PE and PA	< 5 mm	$22.7 \pm 12.1 \times 10^3$ numbers/kg		(Li et al. 2018b)
	Guangdong	E-waste dismantling zone	PS, PP, PVC	< 1 mm	9450 ± 9520 numbers/kg		(Chai et al. 2020)
		Coastal mangrove sediment	PP, PS	50 µm – 5 mm	98.7 particles/kg		(Zhou et al. 2020b)
	Northwest Soils	Plastic film mulched soil	PE	< 2 mm	388.92 particles/kg		(Meng et al. 2020)
	Southwestern Soils	Forest and plantation soil	PE, PP, rayon	< 5 mm	10,975 particles/kg (banana plantations) 1112.5 particles/kg (rubber plantations) 612.5 particles/kg particles/kg (forests)		(Xu et al. 2022)
Iran	Fars	Seasonal agricultural land, rangeland, and dried river	PE, Light density (LD)	40 – 740 µm	67 – 400 particles/kg	MF	(Rezaei et al. 2019)
Spain	Valencia	Cereal field, olive field	Low-density (LD) or high-density (HD) MPs	> 0.05 mm	930 ± 740 particles/kg LD – NO SA 1100 ± 570 particles/kg LD – NO SA 2130 ± 950 particles/kg HD – SA 3060 ± 1680 particles/kg HD – SA	SA	(Berg et al. 2020)
	Murcia	Vegetable farm	Low density MPs		2116 ± 1024 particles/kg		(Beriot et al. 2021)
Sydney, Australia	Oceania	Industrial Soil	PE, PS, PVC	< 1 mm	300 to 67,500 (mg. kg^{-1})		(Fuller and Gautam 2016)
France	Paris	Urban and Sub-Urban Soils	PET, PA, PUR, Rayon,	200 – 400 µm and 400 – 600 µm	Average atmospheric fallout of (mean ± SD) 110 ± 96 particles/m^2 day^{-1} (site 1); atmospheric fallout estimated as 53 ± 38 particles/m^2 day^{-1} (site 2)	AD	(Dris et al. 2016)

Table 1 (continued)

Country	Location	Soil Type/Land Use	Microplastics			Source	References
			Type	Size	Abundance/ Concentration		
Ireland		Waste WWTPs	HDPE, PE, PES, acrylic, PET, PP and PA	> 45 µm	4,196 to 15,385 particles/kg	SA	(Mahon et al. 2017)
Turkey	Adana/Karataş	Agricultural soil	SBR,	55 µm – –5 mm	16.5 ± 2.4 particles/kg		(Gündoğdu et al. 2022)
Pakistan	Lahore	Agricultural soil		55 µm – –5 mm	3712 ± 2156 particles/kg		(Rafique et al. 2020)
		Roadside soil			3915 ± 1499 particles/kg		
Netherlands	Amsterdam	Peat soil	PE, PAC, PA, and Others	< 5 mm	4825.31 ± 6513.85		(Cohen et al. 2021)
India	Karnataka	Riverside soil	PE, PET, PP	0.3 – 5 mm	84.45 particles/kg		(Amrutha and Warrier 2020)
Singapore		Coastal mangrove sediment	PE, PP, nylon, PVC	< 5 mm	36.8 particles/kg		(Nor and Obbard 2014)

SA: Sludge application, *WI*: Wastewater irrigation, *OF*: Organic fertilizer, *LI*: Littering, *MF*: Mulching film, *CT*: Car tires, *RO*: Runoff, *AD*: Atmospheric deposition

Plastic film mulch provides many benefits: controlling weed growth, increasing the soil and air temperature, minimizing soil erosion, reducing evaporation and other water losses, preventing soil splashing, and growing produce quality and yield (Sintim and Flury 2017; Qi et al. 2020; Qiang et al. 2023). Plastic film mulch is another way of adding MPs to soil (Wan et al. 2019; Qi et al. 2020; Qiang et al. 2023) because they are not readily biodegradable (Rillig 2012; Sintim and Flury 2017). (Zhou et al. 2020a) reported the abundance of MPs in the mulched soil with the plastic film (over 570 pieces/kg) compared to the non-mulched (260 pieces/kg) soil. At a cotton field that was mulched for a long time, it was observed that the area covered with the mulch for 5 years, 15 years, and 24 years continuously, the mean abundance of MPs was 80.3 pieces/kg soil, 308 pieces/kg soil, and 1075.6 pieces/kg soil, respectively (Huang et al. 2020). As a result of residual polyethylene mulch film degradation, phthalate esters and di-(2-ethylhexyl) phthalates may form, as well as aldehydes and ketones (Liu et al. 2014). (Wang et al. 2013; Serrano-Ruiz et al. 2021) reported that the agricultural plastic films may be a significant source of Phthalic acid esters (PAEs) contamination in soil and bis-(2-ethylhexyl) phthalate (DEHP), di-n-butyl phthalate (DnBP), and di-n-octyl phthalate (DnOP) were the most abundant phthalate esters. Hence, the primary cause of the harmful impact of microplastics on plants is the microplastics themselves, along with additives like PAEs.

Mostly demanded/used plastic products that are being used and ultimately add MPs to the environment are high-density polyethylene (HDPE), low density polyethylene (LDPE), linear Low Density Polyethylene (LLDPE), biodegradable poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), polyethylene (PE), acrylic (PP&A) fibers, polyvinyl chloride (PVC), polypropylene (PP), polyurethane (PUR), polystyrene (PS), polytetrafluorethylene (PTFE), polyethersulfone (PES), polyethylene terephthalate (PET), synthetic blend rubber (SBR), polyurethane (PU), acrylonitrile butadiene styrene (ABS), styrene butadiene (SBR), expanded polystyrene (EPS), thermo-plastic elastomers (TPE), styrene-acrylonitrile copolymer (SAN), poly methyl methacrylate (PMMA), polycarbonate (PC), and polyamide (PA) (Geyer et al. 2017; Scheurer and Bigalke 2018; Kim et al. 2020b; Ya et al. 2021; Wang et al. 2022b; Qiang et al. 2023).

Impact of MPs on soil's physical properties

Microplastics alter the soil microclimate and atmosphere (de Souza Machado et al. 2018). Microplastics affect soil's physical properties, including texture, structure and aggregate stability, porosity, bulk density, water holding capacity (WHC), saturated hydraulic conductivity, and reduce rainwater infiltration (Liu et al. 2017; Tang 2020; Joos and De Tender 2022; Zhang et al. 2022a; Li et al. 2022b). It was observed that polyester fibers increased the WHC compared to the polyethylene fibers with increasing concentrations (de Souza Machado et al. 2018; Iqbal et al. 2020; Tang 2020; Sharma et al. 2023).

Contradictory results are also observed by (Guo et al. 2022); reduced WHC was observed in clay to a greater extent than in loamy and sandy soils. The decreased WHC indicates that MPs' negative effect exceeded the micropores' positive impact. The decreasing infiltration rate was observed with the increasing MPs, but it still depends on particle size (Guo et al. 2022). In this case, positive effect of soil’s macropores for infiltration increased compared to the negative impact of MPs on filling macropores (Herath et al. 2013). In this case, the positive effect of soil's macropores for infiltration increased compared to the negative impact of MPs on filling macropores (Guo et al. 2022). If small MPs fill the micropores, this will weaken the soil's water retention capacity (Zhang and You 2013; Guo et al. 2022). Despite increasing the soil's surface area, small microplastic particles might also increase its hydrophobic surface area, which induces water repellency, limit capillary flow, and also adsorb hazardous contaminants (Głąb et al. 2016; Xiang et al. 2022; Qiang et al. 2023). In addition, the water repellency of microplastics in soil and delayed wetting caused by "mixed particles" results in more air replacing water molecules in the pores (Głąb et al. 2016). MPs interfere with the accumulation of small soil particles, reducing micropores (Liu et al. 2017).

Reduction in soil bulk density depends on the types of MPs (Li et al. 2022b); polyester fibers show a decrease in the soil bulk density compared to polyacrylic and polyethylene microparticles; incorporation of MPs like PS, PP, PET, PES, or HDPE at the concentration of 2% (w:w) reduce the bulk density (Iqbal et al. 2020; Tang 2020; Joos and De Tender 2022; Sharma et al. 2023). The decline in the bulk density also has benefits like increased or better soil aeration, penetration, and growth of roots (Rillig et al. 2019). These MPs create channels that can facilitate the movement of water. Water will move along the surface of MPs instead of spaces between the pores, and this can lead to increased water evaporation; this evaporation will increase more and more with the increasing concentration of MPs, this can increase dryness and make conditions harsh for the plant growth (Rillig et al. 2018, 2019; Wan et al. 2019; Iqbal et al. 2020). (Zhichao et al. 2015) reported that plastics can restrict the movement of soil water and solutes.

Fine-textured clay soil has good soil structure, is more tightly arranged, and has a large number of micropores (McCauley et al. 2005); as we will add the low concentration of MPs it will increase porosity and it will be beneficial for the crop growth, but it will no longer beneficial if the concentration of MPs will increased (Wan et al. 2019; Cao et al. 2021), increased MPs will surround soil particles this gesture can alter the pore size distribution (Głąb et al. 2016). With a rise in microplastic concentration ($> 1\%$), the cohesion among microplastics, soil particles, and aggregates could progressively result in the encasement of soil particles by microplastics, akin to a "wrapping" effect; this will reduce the interaction between soil particles. In particular, the formation of these "ineffective pores" through the combination of soil and microplastic particles could potentially displace the "effective pores" that naturally occur between soil particles, causing more air to replace the water in pores, further weakening water permeability (Guo et al. 2022).

Desiccation cracking in soil is a complex physical phenomenon affecting strength, stability, and permeability. As water evaporates, the matric suction within the soil rises as its water content decreases, inducing tensile stress within the soil. The formation of shrinkage cracks on the soil surface occurs when tensile stress at the soil surface exceeds the soil's tensile strength. The shrinkage and cracking characteristics of the soil are related to soil liquid limit. For soils with a low liquid limit, the tensile stress in the soil tends to be less than the tensile strength, so desiccation cracks cannot form. Desiccation cracking was observed when 5 and 10 mm plastics were applied, while desiccation shrinkage's increased rate was observed at 2 mm(Wan et al. 2019). It is easier for soil to develop desiccation cracking when large plastics are present. By forming cracks in the soil, soil water evaporates from the deep soil, leading to further shortages of soil water. When water re-saturates the soil after cracking, plastics and other pollutants can migrate into deep soil layers along the crack (Rillig et al. 2017a).

Microplastics can be found in the deep and top soil; top soil provides a favorable environment for their degradation/breakdown (Elbasiouny et al. 2022). Based on the soil structures, MPs can move downward in fine-textured soils. This movement is not significant, but in coarse-textured soils, this movement is possible because of agricultural practices like plowing, desiccation cracking, bioturbation, or preferential flow. Contaminants can also move down through these cracks/desiccation cracking. Generally, these MPs can’t reach the groundwater but may be possible in coarse-textured soils with high water table (Scheurer and Bigalke 2018; Wan et al. 2019; Xiang et al. 2022).

Incorporation of large MPs like microfibers (HDPE, polyester, and polyacrylic fibers) can decline water-stable soil aggregates (de Souza Machado et al. 2018; Boots et al. 2019; Tang 2020; Zhang et al. 2022a; Li et al. 2022b; Qiang et al. 2023). Microplastics like PE can decrease soil sorption capacity, initiate the movement of organic contaminants, and cause soil hardening, which increases input costs (Qiang et al. 2023). If MPs get sorbed to the soil particles or incorporated into soil structure, then these MPs will not be available to plants and soil biota for uptake (Rillig 2012); that's a plus point.

Impact of MPs on soil's chemical properties

Microplastics can affect the soil's pH, EC, and nutrient cycling, ultimately reducing soil fertility (Scheurer and Bigalke 2018; Qi et al. 2020; Tang 2020). MPs can increase soil pH (Qi et al. 2020; Joos and De Tender 2022), but this can vary from soil to soil like PE lower pH in acidic soils and increase pH in alkaline soils (Dissanayake et al. 2022). (Smolders and Degryse 2002) found out that tire debris can raise soil pH. On the other hand, HDPE can decrease soil pH (Boots et al. 2019).

Nutrients in the soil primarily originate from the breakdown of minerals and organic materials. Enzymes are crucial in governing nutrient cycles, serving as vital indicators of soil fertility. Nutrient profiling can be altered by MPs (Tang 2020; Li et al. 2022b; Sharma et al. 2023). As in the nitrogen (N) cycle, there are different processes like mineralization, immobilization, ammonia volatilization, nitrification, and denitrification (Hanif 2023). There are several enzymes like nitrate reductase, nitrite reductase, GOGAT, glutamine synthase, alanine aminotransferase, and glutamate dehydrogenase (Kishorekumar et al. 2020), and MPs target these enzymes, especially urease and acid phosphatase to affect N cycle (Li et al. 2022b). Fei and coworkers found out that PE and PVC stimulated the activities of acid phosphatase and urease, on the other hand, inhibited the fluorescein diacetate hydrolase activity (Fei et al. 2020). Likely, a reduction in the activity of leucine aminopeptidase (involved in the N cycle) and N-acetyl-b-glucosaminidase was observed under the influence of PS and PE (Awet et al. 2018; Bandopadhyay et al. 2019), and plastic film mulch can affect the N cycle and reduce inorganic N contents (Li et al. 2022b). PP presence boosts the urease enzyme's activity, which ultimately can affect N hydrolysis (Huang et al. 2019). Due to the effects of Polylactic acid (PLA), which is a biodegradable plastic, a reduction in Ammonium (NH_4) and increased concentration of nitrate (NO_3^-) and nitrite (NO_2^-) was observed (Chen et al. 2020a; Iqbal et al. 2020), increased concentration of NO_3^- and NO_2^- may lead to the N losses (Hanif 2023).

Microplastics (5% weight/weight) impacted denitrification, increasing N_2O released after a 30-day exposure. This could be attributed to the accelerated rate of NO_3^- reduction facilitated by microorganisms (Ren et al. 2020). On the other hand, MPs didn't show any effect on nitrification, and corn starch and copolyester plastic didn't negatively impact nitrification (Bettas Ardisson et al. 2014; Bandopadhyay et al. 2018).

On the other hand, PA, poly-acrylonitrile, and polyamide can increase the availability of N (de Souza Machado et al. 2019). Contradictorily, phthalate esters can contaminate soil (Iqbal et al. 2020). Prolonged use of plastic mulch can reduce organic matter content and inorganic N. Plastic mulch use for ten years downregulated the gene expression of crucial soil enzymes (sDHA, S-UE, S-b-GC, S-Chi, cbbL, chi-A and b-glu), as well as decrease urease activity (Qian et al. 2018). More importantly, gene abundance related to N_2O reduction (nosZ), denitrification (nirS), and N_2 fixation (nifH) was elevated, while the denitrification gene (nirK) was decreased (Iqbal et al. 2020). Reportedly, in maize (ZTN 182), polymer-coated fertilizer (PCF) and MPs can stimulate the activities of acid phosphatase, urease, phytase, and nitrate reductase activities (Lian et al. 2021). In soil, phytotase catalyzes phytate hydrolysis to release organic phosphorous for plant growth (Lian et al. 2021). Further effect of MPs on enzyme activities can be seen in Table 2.

Microplastics comprise carbon (C), primarily inert C, making them degrade slowly. Several studies are evident that MPs can alter the C cycle and the transport of other nutrients like N and phosphorous (P) with the aid of dissolved organic matter (DOM); reportedly MPs can increase the dissolved organic carbon (DOC), N, and P, PP and PE can increase the DOM by 72–324% (Liu et al. 2017; Qi et al. 2020; Joos and De Tender 2022; Li et al. 2022b). A high concentration of MPs increases the nutrient content of DOM. Polystyrene accumulate the humic substances comprising high molecular weight contents, so the DOM comprises high molecular weight humic substances or humic-like materials (Liu et al. 2017) under the influence of PP MPs higher concentration (7% w:w to 28% w:w; particle size < 180 μm) of dissolved C, N, and P get accumulated in the soil (Liu et al. 2017; Joos and De Tender 2022). Microplastics can harm the enzymes associated with the C, N, and P cycling, like N-acetyl—glucosaminidase, phosphatase, β-D-glucosidase, cellobiosidase, and N- acetyl-β-glucosaminidase (Elbasiouny et al. 2022).

In the presence of MP fibers (0.4% w/w), detrimental effects of MPs were observed on potassium (K), sulfur (S), and magnesium (Mg); on the other hand, increased zinc (Zn) was observed (Lehmann et al. 2019). Microplastics (polyethylene and poly-butylene adipate-co-terephthalate) can increase soil organic carbon (SOC), which works as an energy source for microbes (Iqbal et al. 2020). Inert C in MPs increases their stability, serves as a C pool, and helps microbes cope with pressure (as it can be an energy source for them) (Rillig et al. 2018).

Microplastics can increase the C:N ratio, which increases microbial immobilization (Rillig et al. 2019). It is reported that MPs can absorb chemical substances and transport them (it can also increase the exposure of these substances to soil organisms), like pesticides, heavy

Table 2 Effect of MPs on enzymes activities in soil

MP type	Size/concentration	Soil type	Effects	References
LDPE	0.076 g/kg	Cinnamon soil	LDPE had no significant effect on soil invertase activity, but soil urease and catalase activity were enhanced	(Huang et al. 2019)
	5, 10, 15 g/m^2; 37.13 µm	Loamy sand soil	Elevated enzyme activities linked to the carbon (C), nitrogen (N), and phosphorus (P) cycles	(Lin et al. 2020)
LDPE, PVC	1%, 5%; 678 µm and 18 µm	Loamy soil	It enhanced the urease and acid phosphatase activities while suppressing the fluorescein diacetate hydrolase activity	(Fei et al. 2020)
Polyester	0.1%, 0.3%, 1.0%; < 2 mm	Clayey Nitisol	Laccase and cellulase activities are increased by polyester	(Guo et al. 2021a)
	0.3%;	Sandy loam soil	No alterations in enzyme activity were observed in the organic soil without any additional input. However, enzyme activity decreased when wheat straw was present	(Liang et al. 2021)
	0.4%	Sandy loam soil	Polyester decreased β-glucosidase and phosphatase activities under adequate moisture conditions but increased their activities under drought conditions	(Lozano et al. 2021a)
	0.1%, 0.3%, 1.0%; < 2 mm	Clayey Nitisol	The presence of 1% polyester amplified soil β-xylosidase and laccase activities, whereas both 0.3% and 1% polyester exhibited a reduction in enzymatic activities following thermal treatment	(Guo et al. 2021b)
PP	7%, 28%; < 250 µm	Farmland soil	Increased the phosphatase and β-glucosidase activity; No consistent effect on urease activity	(Yang et al. 2018)
	7%, 28%; < 180 µm	Cultivated loessial soil	Elevated the activities of both phenol oxidase and fluorescein diacetate hydrolase (FDAse)	(Liu et al. 2017)
PP, PE	2% (membranous and fibrous MPs) and 0.2% (microsphere MPs)	Loamy and sandy soil	Fibrous PP and membrane PE reduced urease activity while increasing dehydrogenase and phosphatase activities. On the other hand, membrane PE and microsphere PP boosted dehydrogenase and phosphatase activities, but microsphere PP decreased phosphatase activity	(Yi et al. 2021)
PLA	2%; 20–50 mm	Paddy soil	The enzyme activity was not significantly affected by PLA alone. However, when applied to soil containing straw residue, it reduced the activities of catalase, urease, and β-glucosidase	(Chen et al. 2020a)

Table 2 (Continued)

MP type	Size/concentration	Soil type	Effects	References
PA, PU, PC, PE, polyester, PET, PS, PP	0.4%	Sandy soil	The shape and polymer types had no discernible impact on acid phosphatases. However, the presence of foams led to a decrease in β-D-glucosidase activity	(Zhao et al. 2021)
PU	0.01%, 0.1%, 1%; 4.28 ± 0.75 mm	Farmland soil	Phytase, nitrate reductase, acid phosphatase, and urease activities were elevated	(Lian et al. 2021)
PE	28%; 100 µm	Agricultural soil	As a result of PE, enzyme activities were inhibited and microbial activity was reduced	(Yu et al. 2020)
PE, PHB, PS, PLA PBS, PA	0.2%, 2%; 39–80 µm	Sandy loam soil	Exposure to 2% PHB, PLA, and PBS resulted in heightened catalase, urease, and phosphatase activities. In contrast, 0.2% of MPs reduced phosphatase activity while leaving the activities of catalase and urease remain unchanged	(Feng et al. 2022)
PBHV	10%	Experimental field soil	Because of PBHV, the microplastisphere displayed elevated leucine aminopeptidase and β-glucosidase activities compared to rhizosphere soil	(Zhou et al. 2021a)
PVC	20 mm × 20 mm		Decreased FDAse activity (-1.6% up to -30.7%) and reduced the dehydrogenase activity (-14.9 up to -59.0%)	(Wang et al. 2016)
PS	69.5 ± 0.5 nm	Silt loam	Dehydrogenase activity increase until day 14 Decrease at day 28 and Leucine-aminopeptidase and alkaline-phosphatase activities showed a consistent decline, whereas β-glucosidase and cellobiohydrolase activities increased noticeably at high concentrations	(Awet et al. 2018)

metals, antibiotics, and other xenobiotics, although this adsorption depends on the type of MPs, chemical substances, and environmental conditions, furthermore, MPs can act as a carrier for pathogens (Li et al. 2018a; Rillig et al. 2018; Wan et al. 2019; Yang et al. 2019; Yu et al. 2021c; Zhang et al. 2022a). This adsorption can be beneficial, and those pollutants or chemical substances will be less available to plants and soil biota to uptake; this will be a safe play for soil biota and plants (Rillig et al. 2019). (Yang et al. 2019) reported that MPs like LDPE can transport the pesticide residues to the earthworms, and also promote the input of pesticide residues in soil, and also helps in the transport of glyphosate from the upper soil to the deeper soil (Rodríguez-Seijo et al. 2018b; Yang et al. 2019). Tetracycline and ciprofloxacin, which incorporate carbonyl groups, are superiorly adsorbable to polyamides. As a result of the hydrogen bonds formed between the carbonyl group of the microplastics and its amide group, the microplastics serve as proton donors (Li et al. 2018a). A study revealed that MPs could adsorb heavy metals and contaminated MPs like cadmium (Cd), Zn, nickel (Ni), lead (Pb), silver (Ag), mercury (Hg), iron (Fe), antimony (Sb), and manganese (Mn) (Wang et al. 2022a). Microplastics can also extend the retention time of additional stressors introduced to soils. As a result, prolonged exposure and subsequent adaptation can occur (Sun et al. 2018).

Impact of MPs on soil's biological properties & soil biota

Soil organisms, especially microbial communities, are indispensable for the future of life on Earth. They regulate many ecosystem functions like organic matter decomposition, nutrient recycling, soil-borne disease suppression, toxin removal, and plant growth promotion (Qi et al. 2020; Joos and De Tender 2022). Microplastics can affect the abundance and diversity of soil organisms (earthworms, collembolans, springtails, isopods, nematodes) and also affect the diversity, structure, sustainability of microbial communities, and the activities of microbes (bacteria and fungi) (Rillig 2012; de Souza Machado et al. 2018; Iqbal et al. 2020; Zhang et al. 2020a; Lin et al. 2020; Kim et al. 2020b; Elbasiouny et al. 2022; Joos and De Tender 2022; Li et al. 2022b; Tunali et al. 2023). MPs can affect soil organisms' growth, reproduction, gut microbiota, and mortality because of organ damage, nutritional imbalance, weak immune system, and metabolism (Wan et al. 2019; Zhang et al. 2020a; Kim et al. 2020b).

(Lin et al. 2020) reported that LDPE application in the soil can alter the composition and abundance of microarthropods and nematode communities. Still, the effects of MPs were also observed on the structure and biomass of the microbial community.

Microplastics consumption by earthworms can pass to the food chain, as it plays a vital role in the soil food web (Elbasiouny et al. 2022; Joos and De Tender 2022). Even earthworms can ingest, digest, and transport MPs downward from top soil to deep in the soil profile possibly; they can reach groundwater (Rillig et al. 2017b; Zhang et al. 2020a; Elbasiouny et al. 2022; Joos and De Tender 2022). There are several species of earthworms like *Eisenia fetida, Lumbricus terrestris*, *Eisenia andrei,* etc., on which the effect of MPs has been tested (Joos and De Tender 2022).

Due to the MPs in *L. terrestris*, reduced growth and higher mortality rate were observed, and in *E. andrei*, no harmful effects were observed on their survival, reproduction, and body weight (Huerta Lwanga et al. 2016; Rodriguez-Seijo et al. 2017). Reportedly, PS MPs at the concentration of 1% inhibited earthworm growth, while at the concentration of 0.25–0.5%, no significant effect was observed (Ya et al. 2021; Yu et al. 2021c). A study by (Rillig et al. 2017b) revealed that in the presence of *L. terrestris*, four different sizes of MPs were used; in the presence of earthworms, MPs are found deep in the soil, and this distance can increase as the size of MPs decreases. Moreover, microplastics (MPs) can induce skin lesions and diminish the reproductive rates of earthworms.

In a study conducted on *L. terrestris*, *L. terrestris* were exposed to 0.1% and 1% polyester-derived MPs for 35 days, and dried plant material was used as a food source. The results show that MP ingestion was not lethal to *L. terrestris,* but under the influence of 1% MPs, 1.5 fold decrease in the cast production, 23.4 fold increase of metallothionein-2 (mt2), and 9.9 fold decline in heat shock protein (hsp70) was observed (Prendergast-Miller et al. 2019). In a similar study, the effect of PE MPs was observed on *L. terrestris*, different concentration (0, 7, 28, 45, and 60%) of PE; after 60 days, a higher mortality rate and reduced growth rate was observed in 28, 45, and 60% PE particles (Huerta Lwanga et al. 2016).

Similarly, when *Enchytraeus crypticus* was exposed to two different size ranges of nylon (3–18 and 90–150 µm) and PVC, the ingestion was, although not leather for *E. crypticus*. Still, it affected their reproduction; small-sized nylon particles affected most compared to the large-sized nylon particles; on the other hand, no significant effect of PVC was observed (Lahive et al. 2019). In a separate investigation involving *E. crypticus* subjected to nano-PS plastic exposure, significant alterations were observed in the intestinal microbiota of these soil dwelling organisms. In addition to essential elements cycles, these microbial communities utilize organic substances. Within the intestinal microbiota of *E. crypticus*, there was a notable reduction in

Table 3 Effect of MPs on bacterial community and diversity in soil

MPs	Size/concentration	Soil type/land use	Effect	References
LDPE	76 mg/kg; 0.01 mm	Cinnamon soil	Affected the microbial community composition, No effect on microbial diversity	(Huang et al. 2019)
	200 fragments per 100 g soil,		LDPE altered the soil bacterial community structure, with community differences increasing progressively, intensifying throughout culture time. This enhanced the soil bacterial community succession	(Wang et al. 2020c)
	2%, 7%; 150–250 µm	Experiment station soil	By changing the complexity and modularity of bacteria networks in the soil, LDPE at 2% and 7% influenced the diversity of the soil bacterial community. Furthermore, the *Acidobacteria* abundance increased	(Rong et al. 2021)
	0.1%, 0.5%, 1%, 3%, 6%, 18%	Clay loam soil	Decreased the abundance of nitrite reductase (*nirS*) and ammonia oxidizing bacteria. The abundance of *Amycolatopsis*, *Nocardioidaceae*, *Catellatospora*, *Lentzea*, *Aeromicrobium*, *Mycobacterium*, *Nocardiaceae*, *Pimelobacter*, *Nocardia*, and *Rhodococcus* increased at 18% MPs	(Gao et al. 2021)
Plastic mulching		Field soil (Humus & Eluvial Horizon)	Increased the relative abundance of *Cyanobacteria* but *Acidobacteria*, *Chloreflexi*, *Gemmatimonadetes*, showed opposite trend	(Yu et al. 2021a)
		Field soil	Increased the relative abundance of *Proteobacteria*, *Bacteroidetes*, and *Cyanobacteria,* on the other hand decreased the abundance of *Actinomycetes*	(Qian et al. 2018)
PS and PE	2% (membranous and fibrous MPs) and 0.2% (microsphere MPs); Fibers length: 3 mm; microspheres, 2 mm × 2 mm; microspheres diameter: 800 nm	Loamy and sandy soil	With the addition of PE membranes and PP fibers, bacterial diversity was improved; microbial community structure was altered with the enrichment of Acidobacteria and Bacteroidetes, while Deinococcus-Thermus and Chloroflexi were depleted	(Yi et al. 2021)
LDPE	2000 particles/kg	Cinnamon soil	Increased relative abundance was observed in *Bacteriodietes, Acidobacteria, Nitrospirae, Gemmatimonadetes*, and *Proteobacteria*	(Huang et al. 2019)
PE, PP, PA, PS, PET, and PVC	2% (w/w)	River shore soil	Increased Relative abundance in *Actinobacteria* but decline in *Bacteroidetes* and *Gemmatimonadetes*	(Zhang et al. 2023)
LDPE, PVC	1%, 5%; 678 µm,18 µm	Loamy soil	Increased the microbial community's diversity. *Sphingomonadaceae* and *Xanthobacteraceae* relative abundances decreased, while *Burkholderiaceae* relative abundances increased	(Fei et al. 2020)
HDPE, PLA	0.5% and 10% (w/w)	Farmland loamy soil	Increased abundance of *Actinobacteria*, *Proteobacteria*, *Chloroflexi*, and *Gemmatimonadetes*	(Wang et al. 2022d)
PHBV	10%; Pellets	Field Soil	Altered the composition of the bacterial community across various taxonomic ranks, leading to heightened diversity and an increased relative abundance of the *Acidobacteria* and *Verrucomicrobia phyla*	(Zhou et al. 2021a)

Table 3 (continued)

MPs	Size/concentration	Soil type/land use	Effect	References
PE, PS, PVC	7% and 14% (w/w)	Farmland soil	Increased abundance *Proteobacteria*, *Actinobacteria*, and decreased abundance of *Acidobacteria*	(Fan et al. 2022)
PVC (Film)	0.2%, 0.6%; 0.008 mm	Field Soil	Alkaline soil bacterial communities were more negatively affected by PVC film in terms of composition, diversity, and metabolism	(Liu et al. 2021)
PVC	0.1%, 1%; < 0.9 mm	Red and paddy soils	There was no substantial impact on bacterial diversity and composition. But *Luteimonas*, *Ramlibacter*, and *Bradyrhizobium* abundance increased	(Yan et al. 2021)
	1000 µm		Abundance declined in *Proteiniborus sp.* and *Garciella sp.*	(Wei et al. 2019)
	90 mg particles (3.5 kg soil)$^{-1}$	Tea garden soil	Increased abundance of *Proteobacteria* and *Firmicutes* emerged as a dominant bacterial phylum	(Li et al. 2021b)
PET	0.2% and 0.4% (PET)	Artificial soil	In soil, 2% and 0.4% of PET microplastics (MPs) and 3% of LDPE microplastics (MPs) altered the bacterial composition	(Ng et al. 2021)
LDPE	0.2% and 3% (LDPE)			
PS, PTFE	0.25%, 0.5%; 0.1–1 µm (PS) and 10–100 µm (PTFE)	Rice paddy soil	*Chloroflexi* and *Acidobacteria* abundances increased while *Proteobacteria* abundances decreased	(Dong et al. 2021a)
PLA	2%; 20–50 mm	Agricultural soil	There were no notable alterations in the overall diversity and composition of the bacterial community, nor were there any impacts on associated ecosystem functions and processes. But the dominance of Azotobacter, Nocardioides, Kribbella, Lysobacter, and Sphingomonas increased	(Chen et al. 2020a)
PS, PLA	1% (w/w); 150–180 µm		Decreases the bacterial diversity	(Sun et al. 2022)
PS	0.02–2 µm	Quartz sand	Increased the transport of *Escherichia coli* in soil	(He et al. 2018)
	0.5%; 330–640 nm	Shajiang-Aquic Cambosol	Under two distinct CO2 conditions, microplastics (MPs) had little effect on bacteria, yet they significantly mitigated the detrimental effects of sulfamethazine (SMZ)	(Xu et al. 2021)

Table 4 Effect of MPs on fungal community and diversity in soil

MPs	Size/concentration	Soil type/land use	Effect	References
Polyester	0.4%; 1.70 µm	Sandy loam soil	Arbuscular mycorrhizal fungi colonization increased	(Lehmann et al. 2020)
PE, PLA	0.1%, 1%, 10%; 100–154 µm	Sandy loam soil	The community structure and diversity of the AMF were altered, particularly noticeable at the genus level	(Wang et al. 2020a)
HDPE, PLA	0.1%, 1%, 10%; 100–154 µm	Sandy loam soil	Arbuscular Mycorrhizal Fungi (AMF) community composition and diversity changes were observed, with notable relative abundance changes of the dominant species	(Yang et al. 2021b)
PE	5% (w/w); < 13 µm, < 150 µm	Field soil	Increased abundance of *Ascomycota* was observed, *Acidobacteria*, *Nitrospirae* and *Bacteroidetes* abundance declined	(Ren et al. 2020)
PE, PS, PVC	7% and 14% (w/w)	Farmland soil	Increased abundance of *Ascomycota*, while decreases the abundance of *Basidiomycota*, and *Chytridiomycota*	(Fan et al. 2022)
Plastic fragments		Grassland soil	Increased the abundance of *Mortierellomycota* and *Ascomycota*	(Temporiti et al. 2022)
Plastic mulching		Field soil (Humus & Eluvial Horizon)	Highest relative abundance in Basidiomycota, compared to Ascomycota and Mortierellomycota showed opposite trend	(Yu et al. 2021a)
PS	0.1 mm	Aqueous and atmospheric environment	Polystyrene (PS) encapsulated and initiated cell death in both *Aspergillus oryzae* and *Aspergillus nidulans*	(Nomura et al. 2016)
LDPE	0.1%, 0.5%, 1%, 3%, 6%, 18%	Clay loam soil	Fungal Abundances increased	(Gao et al. 2021)
PET	222–258 µm	Agricultural soil	Polyester and PP increased the root colonization of AMF. Non-AMF and mycorrhizal fungal coils but PET decreased their root colonization	(de Souza Machado et al. 2019)
PP	647–754 µm			
polyester	5000 µm			

Flavobacteria, Rhizobium, and other fungal species when exposed to a high concentration of nano-polystyrene plastic microspheres (10%). Furthermore, this exposure resulted in a corresponding decrease in the weight of *E. crypticus* by 10% (Zhu et al. 2018a).

E. fetida was also exposed to PE and PS at different concentrations for 14 days, at 20% of MPs increased activity of peroxidase and catalase CAT), and the level of lipid peroxidation was observed, contradictorily, the activities of glutathione S-transferase and superoxide dismutase (SOD) were inhibited (Wang et al. 2019b). Huerta Lwanga and his colleagues revealed the presence of LDPE MPs within the soil, earthworm casts, and chicken feces, and the concentration of MPs was increased from soil to earthworm casts and chicken feces. This study brings to light the reality that microplastics (MPs) have gained the capacity to infiltrate and disrupt terrestrial food webs(Huerta Lwanga et al. 2017b). (Zhou et al. 2020c) discovered that earthworms and Cd will decrease their growth and mortality rates. (Zhang et al. 2020b) found out ~ 2 particles/individual PE MPs in earthworms.

According to some theories, the latter effect may result from damage to the male reproductive system. Microplastics consumed by earthworms can trigger the production of nanoplastics (NPs) by interacting with their gut microbiome. These NPs are subsequently released into the environment as smaller plastic particles. Upon excretion, these particles become accessible to other soil-dwelling organisms, such

Table 5 Effect of MPs on microbial community and diversity in soil

MPs	Size/concentration	Soil type/land use	Effect	References
PA, PP, PS, and LDPE	1%; 90–100 mm	Arable Soil	Induced distinct patterns of microbial variation, with bacteria exhibiting a greater degree of variability compared to fungi and protozoa	(Wiedner and Polifka 2020)
PE	0.2%; 0.03 mm	Red soil, fluvo-aquic soil, and paddy soil	Polyethylene diminished the abundance of functional genes and microbial diversity while enhancing the presence of pathogenic microorganisms	(Li et al. 2021c)
	0.2% MPs, 0.02% NPs	Sandy loam soil	Protistan communities were altered by PE, with noticeable shifts only observed in the bacterial communities at specific family levels but not in the fungi communities	(Zhu et al. 2021)
	28%; < 100 µm	Agricultural soil	A change in the diversity and richness of bacterial and fungal communities was observed, e.g., Proteobacteria replaced Actinobacteria as the dominant phylum	(Hou et al. 2021)
	5%; < 13 µm, < 150 µm	Clay Soil	Increasing PE sizes reduced both bacterial and fungi community richness and diversity. In contrast, smaller PE enhanced bacterial and fungal communities in fertilized soil by increasing their richness and diversity	(Ren et al. 2020)
LDPE	2, 10, 15 g/m^2; 37.13 µm	Loamy sand soil	In soil microbial communities, MPs exerted little influence on their biomass and structure. However, they did bring about alterations in soil microbial function	(Lin et al. 2020)
Polyester	0.1%, 0.3%, 1.0%; < 2 mm	Clayey Nitisol	There was little impact on soil bacteria and fungi	(Guo et al. 2021a)
PE, PBS, PS, PHB, PLA, and PA	0.2%, 2%; 39–80 µm	Sandy loam soil	Reduction in bacterial communities' richness and diversity and induced changes in microbial community composition. *Ktedonobacterales* abundance declined; *Rhizobiales* abundance increased	(Feng et al. 2022)
PU	0.01%, 0.1%, 1%; 4.28 ± 0.75 mm	Farmland soil	There were no notable shifts in bacterial diversity, but there was an increased abundance of *Firmicutes*, *Bacteroidetes*, *Verrucomicrobia,* and *Fibrobacteres*	(Lian et al. 2021)
Polyacrylic	18 µm	Agricultural Soil	PA and PS decreased microbial activity while PE had no effect	(de Souza Machado et al. 2018)
Polyester	8 µm			
PE	643 µm			
PS	100 and 1000 ng PS-NPs/g	Agricultural soil	Increased the biomass	(Awet et al. 2018)
PA, PET, polyester, PP, PS, and PEHD	PA: 15–20 µm PET: 222–258 µm Polyester: 5000 µm PP: 647–754 µm PS: 547–555 µm PEHD: > 800 µm	Agricultural soil	PA, PEHD, and polyester increased microbial metabolic activities, on the other hand PET decreased the microbial metabolic activities	(de Souza Machado et al. 2019)

Table 6 Effect of MPs on earthworms

Species	MPs type	Size/concentration	Effects	References
Eisenia fetida	LDPE	0.1, 0.25, 0.5, 1.0, 1.5 g kg^{-1}; < 400 µm	At a concentration of 1.0 g per kilogram (g/kg), microplastics led to surface damage in *E. fetida*, triggering oxidative stress and eliciting neurotoxic responses	(Chen et al. 2020c)
		62, 125, 250, 500, 1000 mg/kg; 250–1000 µm	The presence of microplastics led to alterations in the oxidative stress and energy metabolism of earthworms	(Rodríguez-Seijo et al. 2018a)
	PE and PS	0, 1, 5, 10, 20%; < 300 µm	Earthworm (*Eisenia fetida*) exposed to 20% PE or PS particles exhibited a significant rise in catalase and peroxidase activity, while the activity of superoxide dismutase was suppressed	(Wang et al. 2019b)
	PS	0.25%, 0.5%, 1% and 2% (w/w); 58 µm	Earthworm growth was notably hampered, and mortality rates were heightened when exposed to elevated microplastic concentrations (1% and 2% w/w)	(Cao et al. 2017)
	PE	30 µm, 100 µm	PE heightened the concentration of metals in earthworms, resulting in harm to the earthworms	(Li et al. 2021d)
	PU	< 75 µm	Polybrominated Diphenyl Ether (PBDE) tends to accumulate in organisms that consume soils containing biosolids or discarded plastic waste like PU	(Gaylor et al. 2013)
	PP	< 150 µm; 0.03, 0.3, 0.6, 0.9%	The simultaneous exposure to MPs and Cd had more pronounced adverse effects on *E. foetida*, and MPs had the capability to enhance the availability of Cd	(Zhou et al. 2020c)
Eisenia andrei	PE	1000 mg/kg; 180–212 µm, 250–300 µm	Microplastics influenced the activity of coelomocytes, with more pronounced damage observed in the male reproductive organs compared to females	(Kwak and An 2021)
		0, 62.5, 125, 250, 500, 1000 mg/kg; 250–1000 µm	The average number of earthworm larvae remained consistent across various microplastics treatments after a 56-day exposure period, with no noteworthy distinctions. There was no impact on the survival rate, the quantity of juvenile earthworms, or the ultimate weight of adult earthworms. However, it was confirmed that there were damages and responses in the immune system	(Rodriguez-Seijo et al. 2017; Rodríguez-Seijo et al. 2018a)

Table 6 (continued)

Species	MPs type	Size/concentration	Effects	References
Lumbricus terrestris	Polyester	0%, 0.1%, 1%; 361.6 µm	The ingestion of microfibers (MFs) had no lethal effects on earthworms, and these earthworms displayed no avoidance response towards MFs	(Prendergast-Miller et al. 2019)
	LDPE	7%; < 150 µm	Bacteria derived from the gut of *L. terrestris* were capable of decomposing 60% of microplastics and generating nanoplastics as a byproduct	(Huerta Lwanga et al. 2018)
		1, 5, 10 and 15% v/v; 200–300 µm	Growth rate declined and MPs got concentrated in casts	(Huerta Lwanga et al. 2016)
		7, 28, 45 and 60% w/w; 200–300 µm	The 7% LDPE treatment yielded the highest burrows and the most efficient bioturbation of microplastics (MP)	(Huerta Lwanga et al. 2017a)
	HDPE	0.92 ± 1.09 mm^2; HDPE: 236, 1261, and 4505 mg/kg Zn: 0.6, 3.4, and 12 mg/kg	In gut no retention of HDPE was observed, and no evidence of Zn accumulation, mortality, or weight loss	(Hodson et al. 2017)
	PE	7, 28, 45 and 60% w/w; < 150 µm	Earthworm mortality rised when exposed to 28%, 45%, and 60% microplastics for a period of 60 days, accompanied by a substantial reduction in their growth rate	(Huerta Lwanga et al. 2016)
		710–850, 1180–1400, 1700–2000 and 2360–2800 µm; 750 mg per 2.5 kg soil (added on the soil surface) (2625, 424, 203 and 75 particles per 2.5 kg soil)	Earthworms have the capacity to move MPs within soils through various means, including their casts, burrows (which can impact soil hydraulics), egestion, and adherence to the earthworm's external surface	(Rillig et al. 2017b)
Enchytraeus crypticus	Polyester fiber	0.02%, 0.06%, 0.17%, 0.5% and 1.5% w/w; 12 µm-2.87 mm, 4–24 mm	Little impact on soil invertebrates	(Selonen et al. 2020)
	PS	0%, 0.025%, 0.5% and 10%; 0.05–0.1 µm	*E. crypticus* exposed to 10% polystyrene experienced a significant decrease in body weight, while those exposed to 0.025% showed an increase in reproduction	(Zhu et al. 2018a)
Metaphire californica	PVC		Combined exposure to microplastics and arsenic had several effects. MPs reduced the accumulation of total arsenic and slowed down the conversion of As(V) to arsenite (As(III)). This alleviated the impact of arsenic on the gut microbiota by binding As(V) and reducing its availability, preventing the build-up of As(V) and total arsenic in the gut. As a result, the earthworm experienced lower toxicity. Furthermore, the earthworm's gut microbiota differed significantly from the surrounding soil, likely due to natural selection in their unique gut habitat. Arsenic exposure led to notable changes in the earthworm's gut bacterial communities, with a marked increase in the abundance of the Proteobacteria phylum and the Enterobacteriaceae family	(Wang et al. 2019a)

Table 6 (continued)

Species	MPs type	Size/concentration	Effects	References
Metaphire vulgaris	PE		NPs decreased the arsenic bioaccumulation within the earthworm's body. The interaction between arsenic and NPs led to alterations in the arsenic biotransformation genes (ABGs) profiles within the earthworm's gut	(Wang et al. 2022c)

as smaller decomposers like microarthropods. Springtails exposed to MPs can suffer severe consequences, including reduced mobility and increased mortality. These springtails can also carry the microplastics to deeper soil layers (Joos and De Tender 2022). (Zhu et al. 2018c) reported that when *Folsomia candida* (a collembolan, but informally it is also known as springtail) was exposed to 0.1% PVC MPs, retarded growth and reproduction was observed, and MPs also altered the microbial diversity in the gut of *F. candida* compared to the surrounding soil. Another study on F. candida revealed that the intestinal microbial community gets altered at 0.5% PE MPs, while at 1%, reproduction was reduced by 70.2% (Ju et al. 2019). In isopod *Porcellia scaber*, exposure to MPs did not affect food intake, body weight, or energy intake, even after 14 days of exposure (Kokalj et al. 2018).

In the case of *Caenorhabditis elegans*, MPs are not only ingested by them but also affect/disturb their survival, reproduction (fewer offsprings under the influence of PLA, LDPE, and polybutylene adipate-co-terephthalate (PBAT)), behavior (increased speed, frequency of body bending, and head thrashing), and the blockage of the digestive tract or exert oxidative damage to intestinal tissues. As nematodes were highly dependent on the water films or water-filled pores, MPs can change the soil water dynamics, affecting the performance of nematodes. The maximum MP size that can be ingested by them is 4.4 ± 0.5 µm (Lei et al. 2018b; Lin et al. 2020; Mueller et al. 2020; Joos and De Tender 2022).

In some cases, microbes are used to biodegrade MPs like *Bacillus sp.* Strain 27 and *Rhodococcus sp.* Strain 36 isolated from the mangroves (Auta et al. 2018). On the other hand, some fungi can reduce the hydrophobicity of MPs because some fungi promote the formation of the chemical bond between functional carbonyl, carboxyl, and ester groups (Yuan et al. 2020). Furthermore, some HDPE- fungi, like *Tubegensis* VRKPT1 and *Aspergillus flavus* VRKPT2, like those used for polyethylene degradation (Devi et al. 2015). Effects of MPs on microbial activities or rhizosphere microbiome vary by MPs shape, size, and soil type. Linear plastics affect microbial activities more commonly than non-linear plastics (Iqbal et al. 2020; Qi et al. 2020; Sharma et al. 2023). Microplastics residues affect the wheat's rhizosphere microbiome (Qi et al. 2020). Low density polyethylene (LDPE) can affect microbial communities' structure, cause oxidative stress, and alter energy metabolism; on the other hand, HDPE can affect the activities of microbial communities and reduce the biomass of earthworms (Qiang et al. 2023).

Further effects of MPs on microbial communities (bacteria and fungi, their diversity, and other soil organisms can be observed in Tables 3, 4, and 5. In some cases, microbes and microarthropods degrade MPs and help in the mitigation of soils polluted with plastics (Qiang et al. 2023); the effect of

Table 7 Effects of MPs on collembolans

	Species	MPs Type	Size/concentration	Effects	References
Collembolans & Springtail	*Folsomia candida*	Polyester fiber	0.02–1.5%; 12 µm–2.87, 4–24 mm	Polyester fibers had little effect on soil invertebrates like *F. candida*	(Selonen et al. 2020)
		PE	0.5% and 1%; < 500 µm	Microplastics impeded the reproductive capacity of earthworms and induced significant changes in their gut microbial community, leading to a reduction in bacterial diversity	(Ju et al. 2019)
		PVC	1 g/kg; 80–250 µm	Exposure to microplastics led to a notable increase in bacterial diversity and brought about alterations in the gut microbiota of springtails. Furthermore, it resulted in significant impediments in the growth and reproduction of springtails. Further, they transported the MPs in soil	(Zhu et al. 2018c, b)
	Folsomia candida *Proisotoma minuta*	Urea–formaldehyde microplastic	< 100 and 100–200 µm; 5 mg of the 100–200 µm fraction and 2.5 mg of the < 100 µm fraction	*F. candida* transports larger particles over greater distances and at a higher speed compared to *P. minuta*	(Maaß et al. 2017)
	Lobella sokamensis	PVC	80–250 µm, 8 mg/kg	Restrained movement of *Lobella sokamensis*	(Kim and An 2019)

MPs on soil organisms like earthworms, collembolans, isopods, and nematodes can be seen in Tables 6, 7, and 8. In the gut of larvae insect *Tenebrio molitor,* two strains of bacteria (*Acinetobacter sp.* NyZ450 and *Bacillus sp. NyZ451*) are found; they can help to remove LDPE up to 18% (Yin et al. 2020). Similarly, in the gut of *Plodia interpunctella,* bacteria presence can help to degrade PE films by around 6–10% (Yang et al. 2014). The bacteria genera *Enterobacter*, *Bacillus*, and *Pseudomonas* are frequently encountered in the biodegradation of plastic materials (Zhang et al. 2022a).

Soil organisms can colonize MPs because of their lower density and hardness and seem softer in texture. This colonization can change soil microbial communities' composition, like the increased population of N fixers (*Burkholderiaceae* and *Betaproteobacteriales*) and reduced population of bacteria for xenobiotic biodegradation (*Xanthobacteraceae* and *Sphingomonadaceae*) (Zhang et al. 2022a; Qiang et al. 2023). Another study says that the addition of MPs decreased the abundance of nitrate reductase (*nirS*) and ammonia-oxidizing bacteria, and a little effect of MPs was observed on the functional genes of ammonia-oxidizing archaea, nitrous oxide reductase, and nitrite reductase (*nirK*) (Gao et al. 2021). MPs can affect the root symbiont relationship, including mycorrhizal fungi and N fixers; these changes can affect the plant's growth and diversity as it is contributed by the soil microbial diversity and root colonizing (Rillig et al. 2019; Tang 2020).

(Gao et al. 2021) conducted a study, and he found that CO_2 fluxes increased at 28.67% with the addition of 18% of MPs in soil. These CO_2 fluxes and MPs resistant microbial species (*Amycolatopsis*, *Mortierella*, *Mycobacterium*, *Nocardioidaceae*, and *Aeromicrobium*) had a strong and positively correlated relationship.

Plastic film mulch such as PE decreases the abundance of Proteobacteria and increases Actinobacteria (Zhang et al. 2022a). Plastic mulches increase or decrease microbial activity in the winter and summer seasons, respectively; mulches increase temperature in the winter season that will touch the optimal temperature for microbes, while in the summer seasons, increasing temperature more than optimal will limit microbial activity. The limited available studies indicated higher microbial abundances, increased respiration rates, and elevated enzyme activities in the

Table 8 Effects of MPs on nematodes, isopods, mites, and snails

	Species	MPs type	Size/concentration	Effects	References
Nematodes	*Caenorhabditis elegans*	PS	0–100 mg/kg; 42 and 530 nm	Nematodes exhibit greater sensitivity to larger particles (530 nm) compared to smaller particles (42 nm)	(Kim et al. 2020a)
			1 μg L^{-1}–86.8 mg L^{-1}; 50 and 200 nm	The exposure to nano-polystyrene particles may lead to disturbances in metabolites related to energy metabolism, thereby causing toxic effects	(Kim et al. 2019)
			1 mg/L; 0.1–5 μm	Among the different groups, the 1.0 μm group exposed to a concentration of 1.0 mg/L had the lowest survival rate and showed the most pronounced reduction in body length. Furthermore, this group exhibited significant damage to GABAergic and cholinergic neurons	(Lei et al. 2018a)
Isopods	*Porcellio scaberz*	Polyester fiber	0.02–1.5%; 12 μm-2.87 mm, 4–24 mm	Little impact was observed on *P. scaberz*	(Selonen et al. 2020)
		Plastic bag film and particles from a facial cleanser (PE)	183 ± 93 (cleanser) and 137 ± 51 (film) μm; 4 mg/g dry weight	No effects on either end-point	(Kokalj et al. 2018)
Oribatid soil mite	*Oppia nitens*	Polyester fiber	0.02%-1.5%; 12 μm-2.87 mm, 4–24 mm	Little impact on *O. nitens* was observed	(Selonen et al. 2020)
	Hypoaspis aculeifer	PVC	1 g/kg; 80–250 μm	Transported MPs in Soil	(Zhu et al. 2018b)
Snails	Achatina fulica	PS	28 nm	Ingesting microplastics led to a decrease in the activity of gut microbes in snails and inflicted histological damage on their digestive organs	(Chae and An 2020)
		PET	0.14–0.71 g/kg; 1257.8 μm	The introduction of 0.71 g/kg microfibers (MFs) resulted in harm to 40% of the snail's gastrointestinal wall villi and a concurrent reduction in liver glutathione peroxidase levels and total antioxidant capacity	(Song et al. 2019)

Table 9 Effect of MPs on agronomic crops

Species	MP type	Size/concentration	Effect	References
Sorghum (*Sorghum saccharatum*)	Biodegradable plastic		Affect seed germination rate	(Sforzini et al. 2016)
Wheat (*Triticum aestivum*)	Starch-based biodegradable plastic mulch, LDPE	500 µm – 1 mm (12.5%), 250–500 µm (62.5%), 50–250 µm (25%)	Throughout the vegetative and reproductive phases of the wheat plant, macro- and microplastic remnants affected various parts of the plant. There was a substantial effect of the type of plastic mulch films utilized on wheat growth, with biodegradable plastic mulch having a more pronounced detrimental effect than polyethylene mulch Reduced the number of fruits, reduced the biomass, and increased chlorophyll content	(Qi et al. 2018)
	PS	0.01–10 mg/L	PS had no significant impact on seed germination rates. However, significantly more root elongation occurred for these roots than for the control group ($p < 0.01$). Likewise, substantial increases in carbon and nitrogen contents and plant biomass were observed following exposure to PS	(Lian et al. 2020)
	PP, HDPE, Biodegradable PLA	150 µm, 1000 µm and 4000 µm; 0.1 g/kg, 0.5 g/kg and 1 g/kg	The results revealed that wheat seed germination was reduced across various microplastic exposures, with the average germination inhibition rates following the HDPE > PLA > PP pattern. Microplastics with medium-sized particles and medium-mass concentrations caused the highest average germination inhibition rates, at 5.65% and 4.55%, respectively. On the other hand, low and high particle sizes and mass concentrations of microplastics had less inhibitory effects on wheat seed germination. In particular, microplastic particle size influenced wheat seed germination rates more than anything else	(Zhang et al. 2021b)
	PS and polymethylmethacrylate		At sites of lateral root emergence, polystyrene and polymethylmethacrylate particles penetrate wheat roots through the crack-entry mode. This mechanism, coupled with particle characteristics, enables efficient plastic absorption and subsequent transport from roots to shoots. Increased transpiration rates significantly drive plastic particle uptake, emphasizing the role of transpirational pull as the primary force behind their transport	(Li et al. 2020a)

Table 9 (continued)

Species	MP type	Size/concentration	Effect	References
Wheat (*Triticum Aestivum L.; Xiaoyan 22*)	LLDPE	50 nm; 10, 100, 500, 1000 mg/L	Affected wheat seed germination rate (2.86–20%) at different concentrations, and inhibited wheat bud length	(Lian et al. 2019)
Blackgram (*Vigna mungo L.*)	PE	(0.25, 0.50, 0.75 and 1.0%	A decrease in germination rates was observed following 24 h of exposure, dropping from 83.33% in the control group to 66.67% in the treatment group using 1.00% PE microplastics	(Sahasa et al. 2023)
Broad Bean (*Vicia faba*)	PS	5 mm, 100 nm; 10, 50 and 100 mg/L	The results indicated that *V. faba* catalase (CAT) enzyme activity and root biomass decreased with 5 mm PS-MPs exposure, while SOD and peroxidase enzyme activities increased significantly. A significant growth reduction was observed when 100 nm PS was exposed at the highest concentration (100 mg/L). Further tests revealed that 100 nm PS caused greater genotoxicity and oxidative damage to *V. faba* compared to 5 mm PS. In addition, 100 nm PS accumulated in *V. faba* roots, potentially obstructing nutrient transport pathways through cell connections or cell wall pores	(Jiang et al. 2019)
Rice (*Oryza sativa L.*)	PS	200 nm	Rice seed germination was unaffected by PS MPs, but roots were longer, antioxidant enzyme activity was reduced, and reactive oxygen species were accumulated	(Zhang et al. 2021a)
Rice (*Oryza sativa L. II You. 900*)	PS	13.1%, 18.8%, 40.3%	Reduced the shoot biomass, inhibited the leaves growth, antioxidant defense system got affected, disturbance in metabolic pathways reduced the rice production	(Wu et al. 2020)
Mung bean (*Vigna radiata*)	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	Reduced root and bud length, as well as lowered the seedling fresh weight and moisture content	(Liu et al. 2019)
	PS	28 nm; 0, 10 and100 mg/kg	Nanoplastics inhibited the root growth of mung bean plants and resulted in a buildup of nanoplastic particles inside their leaves	(Chae and An 2020)
Soybean (*Glycine max*)	LDPE	0.5–2 cm mesoplastics; 0.1, 0.5, 1% (w/w)	A significant decline in germination rates of 82.39%, 39.44%, and 26.06% for concentrations of 0.15%, 0.5%, and 1.0% was noted in Soybean	(Li et al. 2021a)

Table 9 (continued)

Species	MP type	Size/concentration	Effect	References
Maize (*Zea mays L.var.Wannuoyihao*)	PE	0.1%, 1% and 10% (w/w); 100–154 µm	The simultaneous presence of PE and Cd had a notable effect on root biomass. PE and PLA led to an elevation in soil pH and DTPA-extractable Cd concentrations in the soil, but it did not result in a change in Cd accumulation within plant tissues. On the other hand, PLA, decreased the chlorophyll content in leaves and maize biomass. A high dose of PLA could potentially pose a significant threat to soil–plant systems by influencing the bioavailability of Cd	(Wang et al. 2020a)
	PLA	10% (w/w); 100–154 µm		
	PS	0, 0.1%, 1%, and 10%; 100–154 µm	The findings indicate that introducing cadmium (Cd) at a concentration of 5 mg/kg led to inhibited plant growth and a notable accumulation of Cd in plant tissues. When used on its own, polyethylene exhibited no significant phytotoxic effects. However, a higher dosage of high-density polyethylene (HDPE) at 10% magnified the phytotoxic impact of Cd. Additionally, polystyrene (PS) had a detrimental effect on maize growth, with the phytotoxicity becoming more pronounced in the presence of Cd. Both HDPE and PS caused an increase in soil diethylenetriaminepentaacetic acid (DTPA)-extractable Cd concentrations but did not significantly alter Cd uptake into plant tissues. In the absence of Cd supplementation, HDPE reduced soil pH, whereas PS had no substantial impact on soil pH. However, when Cd was introduced into the soil, both HDPE and PS elevated the pH levels	(Wang et al. 2020b)
	HDPE			

Table 9 (continued)

Species	MP type	Size/concentration	Effect	References
Common bean (*Phaseolus vulgaris L.*)	LDPE	(0.5%, 1.0%, 1.5%, 2.0%, 2.5% ω/ω dry soil weight	When compared to the control group (with no addition of MPs), LDPE had no notable impact on the biomass of shoots, roots, and fruits. However, when the concentration of LDPE reached 1.0% or higher, there were significant increases in specific root nodules, and only at the 2.5% LDPE level did we observe a significant increase in specific root length. Moreover, the introduction of 1.0% LDPE resulted in a significant expansion of leaf area, while the use of 0.5% LDPE led to a significant reduction in leaf relative chlorophyll content	(Meng et al. 2021)
	Biodegradable MP		In the case of Bio-MPs treatment, when compared to the control group, concentrations of Bio-MPs at 1.5% or higher exhibited a substantial decrease in root and shoot biomass. Furthermore, 2.0% or higher Bio-MP concentrations significantly reduced leaf area and fruit biomass. Across all Bio-MPs treatments showed a significant increase in specific root length and root nodules compared to the control group	

Table 10 Effects of MPs on horticultural crops

Species	MP type	Size/concentration	Effect	References
Cress (*Lepidium sativum*)	Biodegradable plastic		Reduce seed germination rate	(Sforzini et al. 2016; Iqbal et al. 2020; Joos and De Tender 2022)
	PS	50, 500, and 4800 nm;10^3 to 10^7 particles mL^{-1}	When seeds were subjected to 4800 nm microplastics, their germination rate decreased significantly, dropping from 78% in the control group to just 17% in the highest exposure group with 8-h of exposure. After 24-h exposure, the germination rate did not differ significantly	(Bosker et al. 2019)
Tomato (*Solanum lycopersicum L.*)	PE	(0.25, 0.50, 0.75 and 1.0%	Reduction in seed germination rate	(Sahasa et al. 2023)
Tomato (*Lycopersicon esculentum Mill.*)	PET, PP, PE	0.4–2.6 mm; 30,940 ± 8589 particles/kg	The presence of soil containing microplastic sludge had a favorable effect on the growth of tomato plants; however, it caused a delay and reduction in fruit yield	(Hernández-Arenas et al. 2021)
Carrot (*Daucus carota L.*)	PES, LDPE, PA, PC, PP, PU, PET, and PS	< 5.0 mm or 5.0 mm^2; 0.4% (w/w)	After the exposure of 49 days, it was observed that, microplastic films and fibers can slow down seed germination velocity by potentially impacting soil water conditions, thereby potentially disrupting various stages of the seed germination process	(Lozano et al. 2022)
	PP, PC, polyester, PS PE, PU, PA, PET	0.1%, 0.2%, 0.3% and 0.4%	Increased root and soot biomasses	(Lozano et al. 2021b)
	PS	0.1–5 µm; 10 and 20 mg/L	Microplastics measuring 1 µm in size exclusively gathered in the intercellular layer of carrot roots, remaining outside of the cells. Meanwhile, microplastics of 0.2 µm in size were capable of being transported to the leaves Arsenic (As) can lead to the distortion and deformation of cell walls, which in turn enables the entry of PS particles (< 200 nm) into the cells. The presence of both PS and 4 mg L − 1 Arsenic (As) can trigger oxidative bursts within carrot tissue, resulting in a deterioration of carrot quality	(Dong et al. 2021b)

Table 10 (continued)

Species	MP type	Size/concentration	Effect	References
Spring Onion (*Allium fistulosum*)	Polyester	8 µm; 0.2%	Increased the root colonization by AMF, increased root biomass, increased the root tissue density, Decreased the water and nutrient content in leaves, increased the C:N ratio	(de Souza Machado et al. 2019)
	PS	547–555 µm; 2.0%	Increased root biomass, length, and area. Decreased the average tissue density and diameter	
	PA	15–20 µm; 2.0%	Non-AMF structures decreased, decreased the root tissue density, increased the leaf N content and water content. And decreased the C:N ratio and leaf dry biomass. Increased the length and area of roots, and also decreased the average diameter	
	PP	647 – 754 µm	Increased the root area and colonization by AMF, increased the leaf dry biomass, and decreased the leaf water content	
	PET	222 – 258 µm	Decreased the root colonization by AMF, increased root length, root area and the ratio between root and leaf dry biomass, and decreased average diameter of root	
	PEHD	2% (w/w); 643 µm	Increased the root length and root area; Decreased average root diameter	
Onion (*Allium cepa*)	PS	50 nm; 0.01, 0.1 and 1 g/L	Didn’t affected the seed germination rate, but root growth was inhibited at 0.1 and 1 g/L	(Giorgetti et al. 2020)
		25, 50, 100, 200, 400 mg/L and 100 nm	Reduced the root length, ROS production, lowered cdc2 gene expression, and chromosomal abnormalities were observed	(Maity et al. 2020)

Table 10 (continued)

Species	MP type	Size/concentration	Effect	References
Cucumber (*Cucumis sativus L.*)	PS (nanoplastics)	100, 300, 500, and 700 nm; 50 mg/L	Cucumber exposure to 300 nm PS NPs resulted in a notable reduction in biomass. Likewise, 100 nm PS nanoplastics significantly decreased chlorophyll a and b, carotenoid, soluble sugar, and proline levels. In addition, it reduced cucumber leaves' fluorescence. In contrast, cucumber leaves exposed to 700 nm PS NPs exhibited elevated proline levels, hydrogen peroxide content, malondialdehyde, enzyme activity, and peroxidase gene expression. Furthermore, as the particle size of PS nanoplastics increased, there was a corresponding decrease in the relative expression levels and activities of the primary antioxidant enzymes, superoxide dismutase, and catalase. Simultaneously, the content of vitamin C and soluble proteins significantly increased	(Li et al. 2020d)
	PS (nanoplastics)	50 mg/L; 100, 300, 500, and 700 nm	PS particles accumulated in the flowers, stem, leaves, and cucumber fruits and also Increased the Malondialdehyde (MDA) and proline content in the root. The presence of PS NPs of various particle sizes led to a notable rise in soluble protein content within cucumber fruits while concurrently resulting in significant reductions in the concentrations of Mg, Ca, and Fe	(Li et al. 2021e)

Table 10 (continued)

Species	MP type	Size/concentration	Effect	References
Lettuce (*Lactuca sativa L.*)	PVC	PVC-a: 100 nm to 18 µm, PVC-b: 18 to 150 µm; 0.5%, 1%, and 2%	No significant effect was observed on root activity in both PVC-a and PVC-b. Applying 0.5%a and 1%a significantly enhanced root characteristics, including surface area, volume, diameter, and total length. Regarding leaves, PVC a and b had no noteworthy impact on malondialdehyde content. However, using 1%a led to a significant increase in superoxide dismutase activity. PVC-a fostered carotenoid synthesis, while PVC-b inhibited it. Additionally, 1%a diminished the leaf's light energy absorption, dissipation, capture, and electron transfer capacity	(Li et al. 2020c)
	PS, polymethylmethacrylate		Submicrometer- and micrometer-sized polystyrene and polymethylmethacrylate particles can infiltrate lettuce steles through the crack-entry mode, especially at sites where lateral roots emerge. This specific entry mechanism, along with the characteristics of the polymeric particles, facilitates submicrometer plastic absorption. Furthermore, plastic particles are transported from the roots to the shoots. Notably, increased transpiration rates enhance the uptake of plastic particles, highlighting transpirational pull as the primary driving force behind their movement	(Li et al. 2020a)
	PS microbeads	0.2 and 1.0 µm	Nutrient uptake was disrupted, and the tracking of uptake showed that roots had trapped, absorbed, and transported microplastics to stems and leaves	(Li et al. 2019a)
Lettuce (*Lactuca sativa L. var. ramosa Hort*)	PE	23 µm; 0.25, 0.50, and 1.00 mg/mL	The presence of microplastics had a substantial negative impact on the growth rate, chlorophyll content of lettuce, and photosynthesis	(Gao et al. 2019)

Table 10 (continued)

Species	MP type	Size/concentration	Effect	References
Peas (*Pisum sativum*)	PS	40, 20 mg/kg	Reduced crop production, increased nutrient content, and significant changes were observed in color, amino acids, protein, and weight. As MPs enter through incomplete Casparian strips during root development, they travel alongside the vascular bundle's cell walls to reach the plant's aboveground portions	(Kim et al. 2022)

presence of biodegradable plastic mulches (BDMs) compared to PE treatments (Bandopadhyay et al. 2018).

Response of plants

Microplastics affect plants in different ways, hindering seed germination and root growth, causing oxidative stress, inhibiting plant height, low seed setting, reducing plant biomass, inhibiting the water and nutrient uptake, accumulation of MPs in plants, by reducing the photosynthesis rate, altering cell membrane, and by affecting plant-symbiont relationship (Gao et al. 2019; Rillig et al. 2019; Iqbal et al. 2020; Elbasiouny et al. 2022; Li et al. 2022b). Various types of microplastics (MPs) exhibit varying effects on the growth of plants, as demonstrated in experiments involving *Lactuca sativa*, *Triticum aestivum*, *Allium fistulosum*, and *Phaseolus vulgaris*. These effects encompass reduced biomass, altered growth rate/responses, impacts on productivity, and modifications to community structure (Elbasiouny et al. 2022). In addition, microplastics are bound to plant roots by adhesive secretions and accumulate near root-soil interfaces, leading to elevated concentrations of microplastics. Consequently, an increase in the amount of hydrophobic soil particles may negatively impact crop growth by blocking water and nutrient uptake (Lian et al. 2021; Guo et al. 2022).

The mechanism of MPs taken up by the plants is still unclear, but a couple of methods can help with that, like endocytosis, apoplastic transport, and crack-entry mode (Wu et al. 2021). Endocytosis is a broad term that refers to the cellular process by which cells absorb external materials by engulfing or internalizing them with the cell membrane (Flaherty 2012). (Bandmann et al. 2012) reported that nanobeads with the size of 20 nm and 40 nm were engulfed by the BY-2 cells through endocytosis. Only smaller particles can be internalized because of the endocytic vesical's 70 nm to 180 nm diameter. On the other hand, BY-2 protoplast cells can internalize large-sized beads even of 1000 nm.

Once particulate plastics enter plant roots, some particles become trapped within the mucus layer, primarily composed of highly hydrated polysaccharides. This process concentrates the particles on the surface of the roots before they are transported within plant tissues via apoplastic transport. The primary driving force behind apoplastic transport is the transpirational pull, which significantly facilitates the distribution of particulate plastics throughout the plant's tissues. However, the apoplastic route from the cortex to the vascular bundle encounters an obstacle known as the endodermic Kasparian strip, which hinders the penetration of pollutants. Consequently, contaminants on the apoplastic pathway are compelled to traverse the endodermic plasmalemma (Wu et al. 2021). A study on Arabidopsis thaliana revealed that

Table 11 Effects of MPs on grasses, herbs and others

	Species	MP type	Size/concentration	Effect	References
Grasses	Perennial ryegrass (*Lolium perenne*)	Biodegradable PLA	0.1% (w/w); 0.6–363 µm	Reduced the seed germination rate, root biomass, and shoot height Increased the chlorophyll a and b ratio	(Boots et al. 2019)
		HDPE	0.48–316 µm	Due to HDPE, soil pH decreased, root biomass increased, and chlorophyll-a/chlorophyll-b ratio increased	
	Hard fescue (*Festuca brevipila*) *Holcus lanatus* Bushgrass (*Calamagrostis epigejos*)	Polyester	0.4% (w/w);	A community's shoot and root mass decreased from well-watered conditions to drought conditions by ~47% and ~53%, respectively; however, the shoot and root mass increased by ~6% and ~90%, respectively, when microfibers were added to the soil. Improved roots penetration in soil, reduced soil bulk density, and improved aeration. In Europe, invasive species like Calamagrostis and the allelopathic Hieracium became more prevalent in the presence of microfibers. Meanwhile, species like Holcus, which have the potential to promote the growth of other plants, experienced a decrease in biomass	(Lozano and Rillig 2020)
Herbs	*Achillea millefolium* *Hieracium pilosella* *Plantago lanceolata* *Potentilla argentea*				
Others	*Arabidopsis thaliana*	Negatively charged nanoplastics	0.3 g/kg and 1.0 g/kg; 55 ± 6 nm; 71 ± 6 nm	Increased the shoot length, reduced the initial root growth, and decreased the above-ground fresh weight by 41.7% and 51.5% when exposed to 0.3 and 1.0 g/kg polystyrene particles	(Sun et al. 2020)
		Positively charged nanoplastics		Initial root growth decreased, and decreased the chlorophyll content By the apoplast pathway, these particles could be absorbed by a root hair in the mature zone and internalized near the stele	

nanoplastics entered the stele through the apoplastic pathway (Sun et al. 2020).

The mechanisms involved in how plants uptake particulate plastics were studied, revealing a potential pathway for these particles to bypass the apoplastic route and enter wheat (*T. aestivum*) plants. Plant cell wall pores and intercellular plasmodesmata typically have diameters of 3.5–5.0 nm and 50–60 nm, respectively. This means that plastics larger than 5 nm cannot penetrate the plant cell wall, and those larger than 60 nm cannot diffuse into the intercellular spaces (Wu et al. 2021).

However, it was observed that particulate plastics, such as those with a size of 200 nm, managed to breach the cell wall through the root cap mucilage, which trapped them in the root cell wall. During periods of active cell division, the apical meristem tissues exhibited high porosity, allowing the diffusion of particulate plastics through these tissues. Furthermore, some cracks could form between epidermal cells and at lateral root sites during cell separation, potentially providing a path for microplastics (e.g., 2.0 µm) to penetrate the stele. Once within the stele, particulate plastics could be transported to aboveground parts of the plant through the xylem, driven by the transpiration stream (Wu et al. 2021). Polymethylmethacrylate, PE, and PS microplastics enter the stele of the root of wheat and lettuce at the site of lateral root emergence; under the influence of transpirational pull, they can be transported to shoots. It creates an alarming situation for the upper parts of plants that can reach the food chain (Qiang et al. 2023).

Microplastics size, shape, type, and concentration affect the plants differently (Tang 2020; Wu et al. 2021; Yu et al. 2021c; Elbasiouny et al. 2022), as shown in Tables 9, 10, and 11. (Sun et al. 2020) found out that positively charged PS can be uptaken by the plans more compared to the negatively charged ones. The type of plastic film used had a strong effect on wheat growth; it can be affected more by the BDM than LDPE (Qi et al. 2018). In *Vicia faba*, MPs with the size of 100 nm can cause more severe oxidative stress and genotoxic compared to the 5 nm sized MPs, which also block the cell wall pores, resulting in disturbance in the nutrient transport (Jiang et al. 2019).

Moreover, MPs can affect plants at community, individual, and cell levels (Wu et al. 2021). At the community level, MPs can alter the plant synergetic interaction; if it becomes out of balance, few species will dominate the ecosystem functions. For example, in Europe, changed bulk density and increased soil macroporosity under the influence of microfibers. The shoot and root mass of grasses and herbs increased, which can increase *Calamagrotis* invasion, and allelophatic *Heieracium* became a dominant species (Wu et al. 2021).

On an individual scale, MPs can affect the plant's physiological and biochemical properties (Wu et al. 2021). Microplastics inhibit seed germination in cress (*Lepidium sativum*). Microplastics block the seeds' capsules and reduce root growth (Iqbal et al. 2020; Wu et al. 2021; Joos and De Tender 2022). Synthetic fiber and biodegradable PLA also retard seed germination (Tang 2020). Linear Low Density Polyethylene (LLDPE) inhibits seed germination and bud length at low concentrations, but at high concentrations, contradictory behavior was noted; LLDPE increased germination (Qiang et al. 2023). High-density polyethylene (HDPE) suppressed the germination of wheat seeds, but in another study, HDPE didn't suppress the germination of Mung bean seeds but reduced the bud length, root length, fresh weight, and moisture content of the seedlings (Qiang et al. 2023). Further effects of different MPs on seed germination can be observed in Tables 9, 10, and 11. (de Souza Machado et al. 2019) reported the increased root length, area, and biomass in the onion (*Allium fistulosum*) under 2% polyethylene high density (PEHD), PS, PET, PA, PP, and PES. Under the influence of 1% LDPE and 1% starch-based BDM root mass decreased in wheat (*Triticum aestivum*) significantly also affected the above ground and below ground parts of wheat during reproductive and vegetative growth phases. Biodegradable plastic mulches (BDMs) negatively affected wheat growth more than LDPE (Qi et al. 2018).

Microplastics can affect photosynthesis indirectly; MPs can affect the leaves, show sign of inhibited growth, MPs will hinder chlorophyll fluorescence, reduce chlorophyll a and b, imped protein synthesis modulating energy, affect amino acid metabolism, and interferes with the antioxidant defense system of plants. Although, the effect of MPs on leaves remains less significant than on roots (Gao et al. 2019; Wu et al. 2021; Li et al. 2022b).

Microplastics can affect plants on the cell level (Wu et al. 2021). In their 2019 study, Zhang and colleagues showcased a notable reduction in hydroxybenzoic acid levels induced by polystyrene (PS), resulting in changes to cell wall compositions in spinach (*Spinacia oleraceae*) plants, also inducing metabolic reprogramming in leaves and roots at high doses, and induce stronger metabolic reprogramming in leaves compared to the high amount (Zhang et al. 2019). Reactive oxygen species (ROS) serve as vital indicators in investigating cytotoxic effects, capable of causing harm to cellular structures and functions, as highlighted by (Zhang et al. 2011). Frequently, nanoplastics are implicated in the generation of ROS, leading to oxidative stress (when the ROS level exceeds the antioxidative activities of the organisms) in higher plants and algal cells. When exposed to ROS stress, particulate plastics can lead to a downregulation in ROS-related metabolic processes. Moreover, ROS stress may negatively impact a plant's genetic integrity (Wu et al. 2021). While in lettuce (*Lactuca sativa L. var. ramosa Hort*), MPs impact the growth and physiology due to an increased

ROS content in leaves and roots which will lead to increased antioxidant enzymes like SOD and CAT (Gao et al. 2019).

Studies conducted on wheat revealed that when wheat was exposed to PS microplastics, no significant effects of MPs were observed on wheat seedlings, but MPs decreased the accumulation of cadmium and cuprum because of the sorption of these heavy metals to MPs; in this scenario, MPs prevent plants from the toxic effects of heavy metals, and this will improve photosynthesis, increase chlorophyll content, and reduces the ROS accumulation (Zong et al. 2021). Contradictorily, chlorophyll content and dry biomass were decreased in the case of maize under the influence of biodegradable polylactic acids (PLA) at a high dose. At the same time, PE showed no phytotoxicity (Wang et al. 2020a). In another study, when exposed to PE, MPs declined the transpiration rate, nitrogen content, and maize growth (Urbina et al. 2020). Similarly, when *Lolium perenne* (perennial ryegrass) was exposed to PLA, this reduced the germination and suppressed the shoot length; alteration in root biomass was also observed (Boots et al. 2019).

Conclusion

Microplastics and nanoplastics are an emerging global concern, resulting from the range of anthropogenic activities, with the limited understanding of their effects on soil and terrestrial plants. Despite the many benefits of plastics, as per the previous studies, plastics (macroplastics, mesoplastics, microplastics, and nano plastics) presence in the soil will have adverse effects on soil physical (texture, structure, bulk density, water aggregates stability, water holding capacity, and rainwater infiltration) and chemical properties (alter pH, EC, affect nutrient cycling, enzymes activity, and cause the accumulation of heavy metals in plants) of soil. MPs also affect the soil biota, like earthworms, collembolans, springtails, isopods, and microbes (bacteria and fungi).

There are several ways by which these substances could influence plant performance. The effects can be positive or negative; they can increase root growth and heavy metal accumulation in soil biota. These consequences vary depending on the specific plant species involved, potentially resulting in shifts in plant community composition. And it's also depending on the size, shape, and type of microplastics because each can affect the terrestrial ecosystem differentially. Determining the size and direction of these effects across different scales, from individual plants to entire ecosystems, will pose a challenge contingent upon factors such as ecosystem type and the extent and nature of contamination. It is crucial to conduct research to test these effects, as plants play a significant role in the climate system. The impact of microplastics on plants, including their uptake and potential translocation within plant tissues, emphasizes the need for a comprehensive understanding of the implications for food safety and ecosystem health. While some studies suggest possible negative consequences, there is still much to uncover regarding the mechanisms and long-term effects on different plant species.

We must also explore/understand the interaction of MPs, soil, soil organisms, and plants. Once MPs are uptaken, they can enter the food chain; who knows what will result from this move. Who knows how plants and microbes will interact with them? We still don't know much about the impact of MPs on the community structure of microbes and root-colonizing microbes. Very little research is available on it; that's not enough because many cycles and mechanisms work in the soil, as the soil is a complex entity. Many more questions need to be addressed. Even if we keep the rest of the plastic aside and only talk about the biodegradable plastic mulches, we know the short-term impacts and residues in soil, but the long-term effects are still unknown. The relationship between plastics and microbes needs more exploration because different plastic polymers behave differently, even in the case of biodegradable mulches. The additives used in the production of plastic products and their effects on plants are unknown and need more research to explore their interaction with the world underneath the soil surface.

As we navigate the challenges posed by microplastics in our soils and ecosystems, addressing this issue is vital for preserving the health and integrity of our terrestrial environments, safeguarding agricultural productivity, and ensuring a sustainable future for future generations.

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