Science of the Total Environment 954 (2024) 176641

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Multifaceted effects of microplastics on soil-plant systems: Exploring the role of particle type and plant species

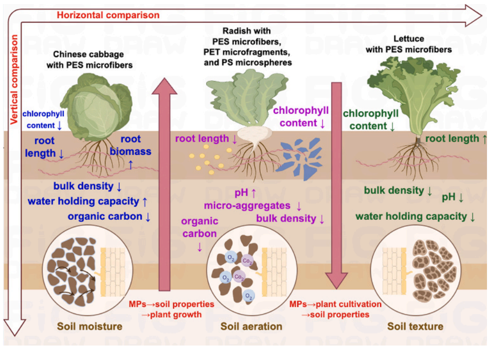
Zhangling Chen [a,b,*], Laura J. Carter [b], Steven A. Banwart [a], Devlina Das Pramanik [c,d], Paul Kay [b]

[a] *School of Earth and Environment, University of Leeds, LS2 9JT, United Kingdom*
[b] *School of Geography, University of Leeds, LS2 9JT, United Kingdom*
[c] *School of Food Science and Nutrition, University of Leeds, LS2 9JT, United Kingdom*
[d] *Centre for Biotechnology and Biochemical Engineering, Amity Institute of Biotechnology, Amity University, Noida, Uttar Pradesh 201301, India*

HIGHLIGHTS

- PS microspheres reduced soil organic carbon by 29.5 %, possibly affecting microclimate.
- PES microfibers lowered soil bulk density by 10.6 %, altering soil structure.
- PS microspheres increased radish germination to 100.0 % by the fourth day.
- PES microfibers boosted cabbage root biomass by 57.4 %, supporting plant growth.
- PET microfragments reduced chlorophyll *b* in radish leaves by 40.9 %, impairing photosynthesis.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Charlotte Poschenrieder

Keywords:
Emerging contaminants
Environmental pollutants
Soil properties
Plant growth
Food safety

ABSTRACT

Microplastics have emerged as a global environmental concern, yet their impact on terrestrial environments, particularly agricultural soils, remains underexplored. Agricultural soils, due to intensive farming, may serve as significant sinks for microplastics. This study investigated the effects of different types of microplastics—polyester microfibers, polyethylene terephthalate microfragments, and polystyrene microspheres—on soil properties and radish growth, while a complementary experiment examined the impact of polyester microfibers on the growth of lettuce and Chinese cabbage. Through both horizontal and vertical comparisons, this research comprehensively evaluated the interactions between microplastic particles and plant species in soil-plant systems. The results showed that polyester microfibers significantly affected soil bulk density, with effects varying based on planting conditions ($p < 0.01$). Polyethylene terephthalate microfragments and polystyrene microspheres reduced the proportion of small soil macroaggregates under radish cultivation ($p < 0.01$). Additionally, polystyrene microspheres significantly altered the total organic carbon stock in radish-growing soil, potentially affecting the microclimate ($p < 0.01$). Interestingly, polyester microfibers promoted lettuce seed germination and significantly enhanced the root biomass of Chinese cabbage ($p < 0.05$). Overall, the environmental effects of microplastic exposure varied depending on the type of particle and plant species, suggesting that microplastics are not always harmful to soil-plant systems and may even offer benefits in certain scenarios.

---

[*] Corresponding author at: School of Geography, University of Leeds, LS2 9JT, United Kingdom.
E-mail address: chenzhangling1101@gmail.com (Z. Chen).

https://doi.org/10.1016/j.scitotenv.2024.176641
Received 31 July 2024; Received in revised form 25 September 2024; Accepted 29 September 2024
Available online 30 September 2024
0048-9697/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Given the crucial role of soil-plant systems in terrestrial ecosystems, and their direct connection to food safety, human health, and global change, further research should explore both the positive and negative impacts of microplastics on agricultural practices.

---

1. Introduction

The global production of plastic has been rising steadily over the past decades, with cumulative plastic production reaching 400.3 million metric tons in 2022 and projected to hit 590 million metric tons by 2050 (Statista, 2024a, 2024b). However, only a small fraction of this plastic is recycled (9 %) or incinerated (12 %), leaving 79 % to accumulate in landfills (Geyer et al., 2017). Due to their high durability and resistance to degradation, plastics persist in the environment and, through an aging process, break down into microplastics (MPs) — particles smaller than 5 mm in diameter (Thompson et al., 2004; Zhang et al., 2022). The continued growth in plastic production suggests a corresponding increase in MP pollution, making it a pressing environmental challenge. While research on the impacts of MPs in aquatic systems is expanding, studies on their effects on terrestrial systems remain limited, despite the fact that approximately 80 % of marine plastic waste originates from terrestrial environments, and the concentration of MPs in soils is 4 to 23 times higher than that in marine systems (Horton et al., 2017; He et al., 2018).

Agricultural land, covering around 38 % of the world's terrestrial surface, has been identified as a major sink for MPs (He et al., 2021). MPs enter agricultural soil through three main pathways: **I) Plastic film mulching (PFM):** PFM is widely used to conserve soil moisture and temperature, thereby improving crop yields. It is estimated that >128,652 km^2 of global farmland is covered with plastic films (Gao et al., 2019), with China alone consuming around 1.4 million tons annually, accounting for over 70 % of global usage (Liu et al., 2014). However, the removal of these plastic films after harvest is both costly and difficult, leading to low recovery rates and massive MP accumulation in soils (Qi et al., 2018). For example, the amount of MPs generated by PFM in northern China increased from 0.32 million tons in 1991 to 1.25 million tons by 2011 (Li et al., 2016). **II) Sewage sludge:** Sewage sludge used as compost contains high concentrations of MPs, with 15,385 items/kg found in samples from wastewater treatment plants (Mahon et al., 2017). A significant proportion of these MPs, primarily polyester (PES) fibers, originate from washing clothes. Studies estimate that in Europe and North America, 63,000 to 430,000 tons and 44,000 to 300,000 tons of MPs, respectively, enter agricultural soils through sludge application (Nizzetto et al., 2016). **III) Wastewater irrigation:** Domestic wastewater, containing MPs such as cosmetic microbeads, washing machine fibers, and fragments of macroplastics, is often poorly treated before being used for irrigation (Huang et al., 2020; Zhou et al., 2021b). Even after wastewater treatment, MPs remain in the effluent, with 124–308 mg released from washing 1 kg of laundry (De Falco et al., 2019). This wastewater is then applied to agricultural lands, contributing further to MP contamination.

The soil-plant system is an indispensable component of terrestrial ecosystems, supporting global biodiversity and ensuring food security for humans (Rillig et al., 2019a). Recent studies show that MPs can have diverse effects on soil-plant systems, depending on factors such as particle shape, size, concentration, surface characteristics, soil texture, and plant species (Lozano and Rillig, 2020; Rillig et al., 2019b). For instance, PES microfibers have been found to reduce soil bulk density and increase water holding capacity (WHC) (de Souza Machado et al., 2018), though another study reported a decrease in WHC but an increase in water stable aggregates (WSA) (Zhang et al., 2019). MPs have also been shown to influence soil element content: exposure to MPs significantly increased soil organic carbon (SOC) and dissolved organic carbon (DOC) content, indicating that MPs may influence global carbon storage by altering soil carbon cycling (Xiang et al., 2024). Additionally, polylactic acid (PLA) biodegradable plastics were found to alter nitrogen cycling (Chen et al., 2020). MPs can also affect plant growth. For instance, perennial ryegrass (*Lolium perenne*) exposed to microfibers exhibited lower germination rates compared to control groups (Boots et al., 2019). Similarly, mung bean roots showed an 83.3 % reduction in growth when exposed to polystyrene (PS) microspheres (Chae and An, 2020). Additionally, PS particles were found to significantly reduce the chlorophyll content in Chinese cabbage (Yang et al., 2021). Conversely, some studies have observed positive effects, such as an increase in root biomass in spring onions (*Allium fistulosum*) when exposed to both PES and PS MPs (de Souza Machado et al., 2019).

Notably, several of the studies mentioned above utilized hydroponic systems, where higher evaporation rates and more mobile particle transport occur than would typically be seen under field conditions (Khalid et al., 2020). However, soil is the primary medium for most terrestrial plants. Further research employing soil incubation is needed to understand the full extent of MP impacts within soil-plant systems. Our study comprises two soil incubation experiments, with the aim of achieving three objectives: (1) to examine how different types of MPs influence soil physical and chemical properties; (2) to evaluate the effects of MPs on plant growth parameters; and (3) to investigate the interactions between MP types and specific plant species, focusing on their combined effects on soil health and plant development. Based on these objectives, we hypothesized that (i) different MP types have distinct impacts on soil properties, (ii) MP particles negatively influence plant growth, and (iii) the interaction between MP types and plant species exhibits varied outcomes in terms of soil-plant health. Through horizontal and vertical comparisons, this study provides crucial insights for ecotoxicological assessments related to soil and terrestrial higher plants, highlighting the importance of considering plastic-type and species sensitivity when evaluating the risks associated with MPs in agricultural environments.

2. Materials and methods

2.1. MP selection and characterization

Three types of MPs were selected in this study: PES microfibers, polyethylene terephthalate (PET) microfragments, and PS microspheres. The selection of these specific types was based on their environmental relevance and physicochemical characteristics. The original PES fiber strand was purchased from James Heal, United Kingdom, while PET microfragments were made from plastic bottles. To produce the MPs, the fiber strands and plastic bottles were manually cut using sharp scalpels and scissors, with a predefined upper size limit of 5 mm (Lozano and Rillig, 2020; de Souza Machado et al., 2019; Lozano et al., 2021). Before incorporating into the soil, all MPs were sterilized to eliminate potential microbial contamination. The PES microfibers and PET microfragments were soaked in a 10 % sodium hypochlorite (NaClO) solution for 5 min, then thoroughly rinsed with deionized water to remove any chemical residue and dried with filter paper. The 5 μm red fluorescent PS microspheres were ordered from Jiangsu Zhichuan Technology Co., Ltd., China. These microspheres were suspended in deionized water at an initial concentration of 25 mg/mL. Additional details regarding the PS microspheres are provided in the supplementary material (Text S1 and Figs. S1–3).

2.2. MP dyeing and measurement

The detection of MPs in soil-plant systems presents great challenges, and fluorescence labeling has emerged as the most promising technique to overcome this barrier (Jiang et al., 2019; Li et al., 2020; Lian et al., 2020). In this study, we employed 1,3,6,8 pyrene tetra sulfonic acid (PTSA), a novel organic fluorophore, to stain PES microfibers and PET microfragments. To prepare the fluorescent dyes, a concentrated PTSA solution was made by dissolving 5 mg of the dye in 80 mL of deionized water. In each amber Duran bottle, 50 mL of deionized water was combined with 250 μL of the concentrated PTSA solution, along with 8.88 g of artificial seawater salt. After adding the MPs, deionized water was used to cover all samples, and the suspension was stirred at 110 rpm intermittently for 24 h. The stained samples were washed three times with deionized water to remove any chemical residues and then dried with filter paper to minimize the potential impact of PTSA on soil and plant health. Additionally, the binding efficiencies between the dye and selected MPs, as well as the location of these stained MPs in the soil, were examined and identified using an EVOS Auto FL 2. The images show no significant dye leakage (Figs. S4–7). Based on the captured images, we utilized ImageJ software to assess the dimensions of PTSA-stained microfibers and microfragments. The average dimensions for microfibers and microfragments used in the experiment were 48.14 ± 10.43 μm and 1.43 ± 0.23 mm, respectively.

2.3. Soil preparation and cultivation

Kettering loam soil was selected as the substrate in this study due to its balanced texture, nutrient retention capacity, and representativeness in agricultural settings (Lozano et al., 2021; Botyanszká et al., 2022). This soil was sourced in 25 kg bags from Pitchcare, United Kingdom. According to the manufacturer, the soil has a pH of 6.8, an SOC content of 2.5 %, and a cation exchange capacity (CEC) of 18 cmol/kg. Before use, the soil was sieved through a 2 mm mesh, air-dried, and homogenized. MPs were then mixed with the soil in a tray by manually stirring to achieve a uniform distribution (de Souza Machado et al., 2019).

2.4. Experimental setup

Two 50-day soil incubation experiments were conducted consecutively in a greenhouse tent (Fig. S8). Throughout the growth period, environmental conditions were maintained at a 12:12 day/light cycle with a temperature of 19 °C. MPs were incorporated into the soil to reach a starting concentration of 100 mg/kg and each experiment also included a control treatment without MPs (0 mg/kg). Each treatment was replicated ten times, and the concentration was selected based on previous studies (Li et al., 2020; Chae and An, 2020; Jiang et al., 2019; Zhou et al., 2021a). Lettuce (*Lactuca sativa*), Chinese cabbage (*Brassica rapa subsp.*), and radish (*Raphanus sativus*) seeds were obtained from Mr. Fothergill's, United Kingdom. Before sowing, all seeds were sterilized with 10 % NaClO solution for 5 min, then washed three times with deionized water to remove any chemical residues and dried with filter paper. Three prepared seeds were sown in each glass jar (diameter: 8.5 cm, height: 9.4 cm), and once the seedlings developed two true leaves, thinning was conducted by removing all but the most vigorous seedling in each container.

2.5. Evaluation of soil property endpoints

After 50 days, plant material was harvested, and bulk soil was collected for soil property analysis. Soil pH was determined by adding deionized water to 10 g of air-dried soil. Bulk density was measured using professional tins (diameter: 8 cm, height: 5.2 cm), with soil samples dried at 105 °C for 48 h. WHC and WSA were assessed according to established protocols detailed in the supplementary material (Texts 2–3). Total organic carbon (TOC) and nitrogen content were determined via high-temperature combustion using an Analytik Jena Multi NC2100S instrument with an NDIR detector. Briefly, 30 μL of 15 % hydrochloric acid (HCl) was added to 10 mg of prepared soil that had been ground to <100 μm using a mixer mill. Subsequently, the samples were dried in an oven at 80 °C for 24 h and encapsulated in silver capsules before analysis.

2.6. Evaluation of plant performance endpoints

The germination rate was recorded from sowing to the seventh day of growth. After harvest, plants were carefully removed from glass jars using a spatula, roots were excised with a sharp scalpel, and adhering soil was washed away with deionized water and dried using a paper towel. Samples were then positioned on a sterilized bench with a scaled ruler placed vertically adjacent to the root, and high-resolution images were captured. Root length was measured using ImageJ software based on the acquired images. Washed plant roots were then dried at 60 °C for 72 h to determine root biomass (Lozano and Rillig, 2020; Lozano et al., 2021). Chlorophyll content was extracted using 90 % acetone, and the absorbance of the supernatant at 664 nm and 647 nm was measured using a Jasco Scanning Spectrophotometer. Chlorophyll *a* (Chla), chlorophyll *b* (Chlb), and total chlorophyll content were calculated using equations proposed by Jeffrey and Humphrey (1975) (Text 4).

2.7. Statistical analysis

Statistical differences between groups were determined using one-way ANOVA followed by Duncan's post hoc test in IBM SPSS Statistics 27. Results are presented as mean ± SD (Standard Deviation). A p-value of <0.05 was considered statistically significant. Figures were drawn using OriginPro2021.

3. Results and discussion

3.1. Effects of different MPs on soil properties under radish planting

Previous studies have confirmed that different types of MPs can cause variations in soil pH (Zhao et al., 2021). For instance, Wang et al. (2020) reported a decline in soil pH due to the presence of PVC MPs. Such changes in pH may result from MPs affecting CEC, which facilitates proton mobility in soil water, a phenomenon attributed to the large surface area and potential reactivity of these plastic particles (Boots et al., 2019). In contrast, Boots et al. (2019) found no significant effect on soil pH when PS MPs were added, attributing this to the composition of PS particles (primarily carbon and hydrogen), which are less likely to induce biogeochemical modifications (de Souza Machado et al., 2019). In our study, we also observed no significant effect on soil pH with the addition of various MPs ($p > 0.05$, Table S1). However, PS microspheres led to a 1.2 % increase in soil pH ($p > 0.05$, Table S1). This could be partially attributed to the fluorescent dye used for staining the PS microspheres, which might have induced specific pH alterations. Nile red, a hydrophobic fluorescent dye commonly used to stain MPs, can interact with soil organic matter and other hydrophobic substances, potentially affecting microbial activity and chemical reactions (Maes et al., 2017; Shim et al., 2016). For example, Nile red may alter soil pH by influencing the degradation process of organic matter (Shim et al., 2018). Additionally, the persistence of Nile red and its degradation products in the soil could modify the chemical environment, leading to an increase in pH (Liu et al., 2019).

MPs such as PS and PET particles are composed of approximately 90% carbon, contributing a substantial source of non-plant-derived carbon when incorporated into the soil (Rillig, 2018). Our study observed a significant reduction in TOC content by 29.5 % following the addition of PS microspheres ($p < 0.01$, Fig. 1A and Table S1), potentially due to the specific plant cultivation conditions. This finding is consistent with Zang et al. (2020), who demonstrated that PVC MPs can influence carbon allocation within soil-plant systems. Over time, as plastic particles accumulate, the carbon within these polymers may establish a carbon reservoir in the soil, potentially transforming it into either a net

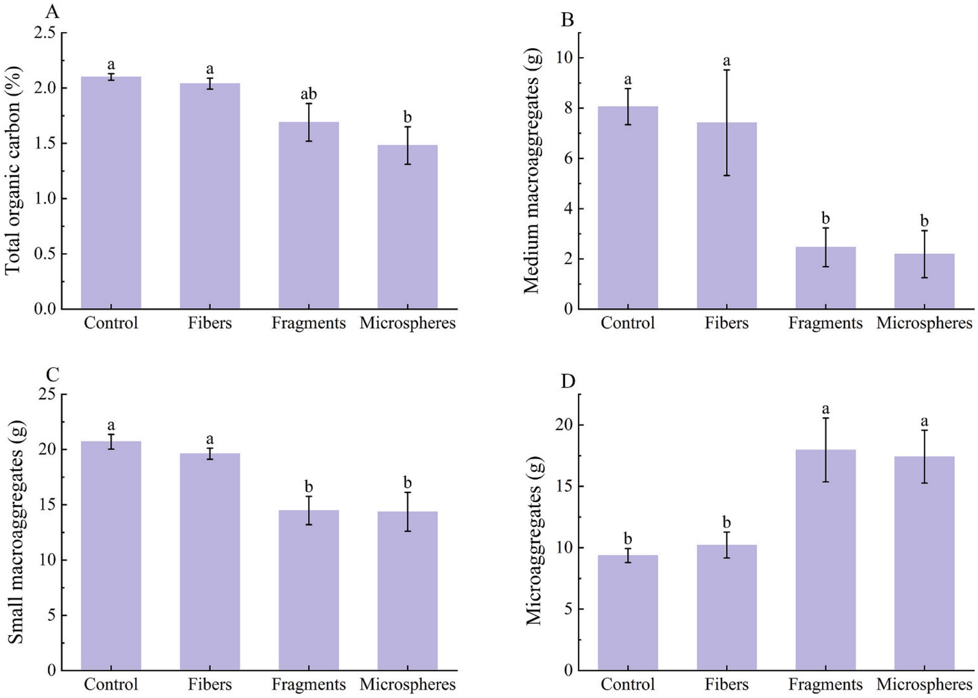


Fig. 1. Soil physical and chemical properties under radish cultivation with exposure to various MPs. (A) TOC content; (B) Proportion of medium aggregates (1000–2000 μm); (C) Proportion of small macroaggregates (250–1000 μm); (D) Proportion of microaggregates (53–250 μm).
*Letter labels (e.g., a, b, ab): Applied in Duncan's post hoc test to denote specific group differences. Groups sharing the same letter are not significantly different, whereas those with different letters exhibit significant differences.

source or sink of CO_2. Thus, MPs could alter long-term carbon storage and cycling, with implications for global carbon dynamics and climate change (Tang et al., 2023; Rillig et al., 2019b; Zhou et al., 2020). Additionally, MPs may affect oxygen availability by altering soil water content or reducing porosity, which could hinder denitrification processes and modify N_2O emissions (Boots et al., 2019; Jiang et al., 2016). Although our research did not detect any significant effects of MPs on soil nitrogen content ($p > 0.05$, Table S1), in line with Chen et al. (2022), this might be related to the specific types of MPs examined. Certain plastics, such as fibers, do not contain nitrogen in their pure form (de Souza Machado et al., 2019), which could explain the lack of impact. However, it is important to consider that MPs could influence nitrogen levels in the soil over time. For instance, Xiang et al. (2023) found that MPs decreased nitrate nitrogen (NO_3^--N) concentrations, particularly at elevated temperatures, suggesting potential long-term effects on nitrogen cycling, plant nutrient uptake, and food production. Furthermore, the leaching of chemicals from MPs may promote the production of methane (CH_4) and ethylene (Romera-Castillo et al., 2018; Sun et al., 2020; Oertel et al., 2016). Given that CO_2, N_2O, and CH_4 are the three most significant greenhouse gases (GHGs), future research should focus on assessing the potential influence of MPs on GHG emissions. These impacts are crucial for climate change and could have detrimental effects on the ecosystem's regulatory services.

The addition of PET microfragments and PS microspheres led to reductions in soil WHC by 6.4 % and 11.5 %, respectively, compared to the control group (Table S1). This decrease in WHC can be attributed to the similarity in size between PET and PS particles and natural soil particles, which may disrupt soil structure and limit the soil's ability to retain moisture (de Souza Machado et al., 2018). Similarly, Wang et al. (2024) found that MPs occupy pore spaces, thereby reducing soil porosity and water retention. Additionally, hydrophobic MPs, such as PS microspheres, further repel water, exacerbating the reduction in WHC (Yu et al., 2023). We also observed significant differences in the proportions of medium macroaggregates ($p < 0.05$), small macroaggregates ($p < 0.01$), and microaggregates ($p < 0.05$) among the PET microfragments, PS microspheres, and the control group (Fig. 1B-D). Specifically, the proportions of medium macroaggregates decreased by 69.5 % and 72.8 % for PET microfragments and PS microspheres, respectively, while the proportion of small macroaggregates decreased by approximately 30.0 %. In contrast, the proportions of microaggregates increased by 91.7 % and 85.8 % for the PET microfragment and PS microsphere treatment groups, respectively (Table S2). These results indicate that MPs interfere with the formation of soil aggregates, a process essential for maintaining soil structure and stability. The breakdown of macroaggregates may result from mechanical disruption caused by MPs, which hinders the natural cohesion of soil particles (Rillig et al., 2017). Furthermore, macroaggregates typically contain more organic matter and provide better habitats for microorganisms. The disintegration of these aggregates may lead to reductions in microbial biomass and activity, thereby affecting nutrient cycling and organic matter decomposition (Lehmann and Kleber, 2015). The shift toward smaller aggregates may also decrease soil stability, increasing the risk of erosion, as microaggregates are more easily displaced by water or wind (Zhang and Liu, 2018). This instability could have profound implications for soil fertility and long-term productivity, particularly in agricultural systems that rely on healthy soil structure. In contrast, we observed no significant impact of PES microfibers on soil WHC or WSA ($p > 0.05$, Tables S1-2). This outcome may be due to the unique physical and chemical properties of PES microfibers, which are more flexible and less prone to fragmentation (Xu et al., 2020; Zhang et al., 2019). These findings differ from previous studies (Yu et al., 2023; de Souza Machado et al., 2018), suggesting that the discrepancies could result from variations in soil texture and characteristics, as different soil types exhibit varying affinities for PES microfibers (Ingraffia et al., 2022b).

Our findings support the first hypothesis that (i) different MP types have distinct impacts on soil properties such as pH, TOC content, WHC, and WSA. These variations may be attributed to the inherent differences in the characteristics of the MPs themselves.

3.2. Effects of PES microfibers on soil properties, under different planting conditions

The presence of PES microfibers induced variations in soil pH across different plant cultivations ($p < 0.05$, Table 1). However, no significant difference in soil pH was observed when comparing the same plant treated with or without PES microfibers ($p > 0.05$, Table 1). This finding aligns with Chen et al. (2022), who suggested that the impact of MPs on soil pH depends on the specific crops planted and their fertilization practices. PES microfibers significantly affected bulk density in radish-growing soil, leading to a decline of 10.6 % ($p < 0.01$, Table 1). A slight reduction in soil bulk density was also noted in other plant treatments, though this was not statistically significant ($p > 0.05$, Table 1). This consistent reduction supports de Souza Machado et al. (2018), who demonstrated that PES MPs decrease soil bulk density regardless of the crop. These variations may be due to the generally lower density of plastics compared to natural soil minerals. For instance, in de Souza Machado et al.'s (2018) study, the control soil had a bulk density of approximately 1439 ± 86 kg m^{-3}, while PES's density was about 1370 kg m^{-3}. Moreover, the linear shape, size, and flexibility of the fibers may enhance their ability to entangle soil particles easily (Rillig et al., 2019b; Zhang and Liu, 2018).

Conversely, the impact of PES microfibers on soil WHC under different planting conditions was minimal ($p > 0.05$, Table 1). This may be attributed to the high hydrophobicity of PES microfibers, which limits their ability to absorb and retain water in the soil (Dris et al., 2016). Additionally, the particle composition and pore structure of the soil may mask the influence of microfibers, rendering their effect on water retention capacity insignificant (Lehmann and Kleber, 2015). No significant differences were observed in carbon and nitrogen contents across different plant cultivations ($p > 0.05$, Table 1). This stability may be explained by the mechanical strength and chemical resistance of PES microfibers, making them relatively stable in the soil environment and less prone to degradation or chemical reactions, thus exerting minimal impact on soil carbon and nitrogen cycles (Rillig et al., 2017). Furthermore, plant root exudates and microbial activities may buffer the presence of microfibers (Bais et al., 2006).

The effect of PES microfibers on soil WSA was plant-dependent. Although the proportions of macroaggregates and microaggregates varied with different plant species, most effects were not statistically significant ($p > 0.05$, Table S3). This may be because plants play a crucial role in mitigating the impact of MPs on soil structure through root-mediated mechanisms, including physical entanglement and chemical interactions via root exudates (Hallett et al., 2009).

3.3. Effects of different MPs on radish growth

The promotion of radish germination in the presence of PS microspheres was clear, with a 100.0 % germination rate observed by the fourth day of sowing, compared to 0 % in the control group. Similarly, PET microfragments facilitated early-stage germination, achieving a germination rate of 86.7 % by the seventh day, compared to 76.7 % in the control group (Fig. 2A). The alteration of soil structure by PS microspheres, such as improved water retention leading to consistently higher soil moisture levels, may explain the accelerated germination (Ma et al., 2010; Rico et al., 2011). Additionally, emerging research suggests that MPs may increase soil temperature by absorbing solar radiation due to their unique properties. This rise in temperature stimulates microbial activity and nutrient mobilization, further accelerating germination (Miralles et al., 2012). However, Bosker et al. (2019) reported that PS microspheres inhibited wheat germination. Ultimately, germination rates appear to be influenced by multiple factors, including the size and shape of the MPs, the plant species, and the cultivation environment, which may explain the varied results reported in the literature.

Although the observed differences were not statistically significant, all types of MPs caused a reduction in radish root length ($p > 0.05$, Fig. 2B). The root length of radish was most affected by the addition of PES microfibers, leading to a 34.5 % decrease compared with the control group (Table S4). PS microspheres exhibited the most pronounced effect on radish root biomass, resulting in a 68.9 % reduction compared with the control group ($p > 0.05$, Fig. 2C and Table S4). The impediment to plant root performance is attributed to mechanical blocking, where the larger size of MPs prevents their entry into plants, leading to massive accumulation on root surfaces (Iqbal et al., 2023b, 2024). This accumulation can hinder the plant's nutrient and water absorption, thus inhibiting growth (Kalčíková et al., 2017). Furthermore, the rough and hydrophobic surface characteristics of MPs may attract other pollutants like heavy metals and pathogenic bacteria (de Souza Machado et al., 2019; Lozano et al., 2021). Some studies have shown that MPs can prolong soil moisture retention, while the use of enclosed containers in our experiments might have exacerbated the negative impact on root growth by fostering potential synergies between MPs and other external pollutants (Iqbal et al., 2023a). Additionally, it cannot be discounted that contaminants such as plasticizers and nonylphenols may influence plant development (Ingraffia et al., 2022a). The inhibitory effect on plant roots is inconsistent with previous studies (Ren et al., 2021; Lian et al., 2020). This discrepancy could be attributed to the utilization of microscale spheres rather than nanoscale counterparts. Meng et al. (2021) proposed that nanoscale PS-MPs could efficiently bind nutrients and activate competition for nutrients between plant roots and microbial communities, thereby promoting root growth. In addition, the enhancement of plant biomass by nanoscale spheres might be ascribed to their capacity to enter plant tissues through a crack-entry mode (Li et al., 2020). However, microscale plastics may not have the above functions due to their relatively larger size. Of course, this also has to do

Table 1
The effects of PES microfibers on soil physical and chemical properties under different planting conditions.

Treatment	pH	Bulk density (g/cm^3)	WHC (%)	Carbon content (%)	Nitrogen content (%)	C/N ratio
CK-Lettuce	7.66 ± 0.02^{bc}	0.52 ± 0.02^{cd}	82.00 ± 4.47^{a}	2.05 ± 0.13^{a}	0.23 ± 0.01^{ab}	8.83 ± 0.24^{ab}
MPs-Lettuce	7.58 ± 0.05^{c}	0.49 ± 0.04^{d}	77.00 ± 5.70^{a}	2.06 ± 0.21^{a}	0.23 ± 0.03^{ab}	9.03 ± 0.20^{ab}
CK-Cabbage	7.78 ± 0.03^{a}	0.56 ± 0.06^{bc}	77.00 ± 4.47^{a}	2.12 ± 0.19^{a}	0.24 ± 0.02^{a}	8.70 ± 0.18^{a}
MPs-Cabbage	7.79 ± 0.10^{a}	0.55 ± 0.06^{bcd}	80.00 ± 3.54^{a}	1.96 ± 0.21^{a}	0.22 ± 0.02^{ab}	9.11 ± 0.25^{ab}
CK-Radish	7.74 ± 0.08^{ab}	0.66 ± 0.02^{a}	78.00 ± 6.71^{a}	2.07 ± 0.05^{a}	0.23 ± 0.02^{ab}	8.94 ± 0.81^{ab}
MPs-Radish	7.74 ± 0.08^{ab}	0.59 ± 0.03^{b}	78.00 ± 4.47^{a}	2.04 ± 0.10^{a}	0.21 ± 0.02^{a}	9.81 ± 0.64^{b}
F	6.856	9.914	0.773	0.542	1.682	3.606
p	0.000	0.000	0.578	0.743	0.177	0.014

*CK: The control treatment without PES microfibers; MPs: The positive treatment with the addition of 100 mg/kg PES microfibers.

*Results are presented as mean ± SD (Standard Deviation).

*F-value: Indicates the ratio of between-group variance to within-group variance, assessing whether significant differences exist between groups.

**p*-value: Reflects the statistical significance of the observed differences; a smaller *p*-value suggests significant differences.

*Letter labels (e.g., a, b, ab): Applied in Duncan's post hoc test to denote specific group differences. Groups sharing the same letter are not significantly different, whereas those with different letters exhibit significant differences.

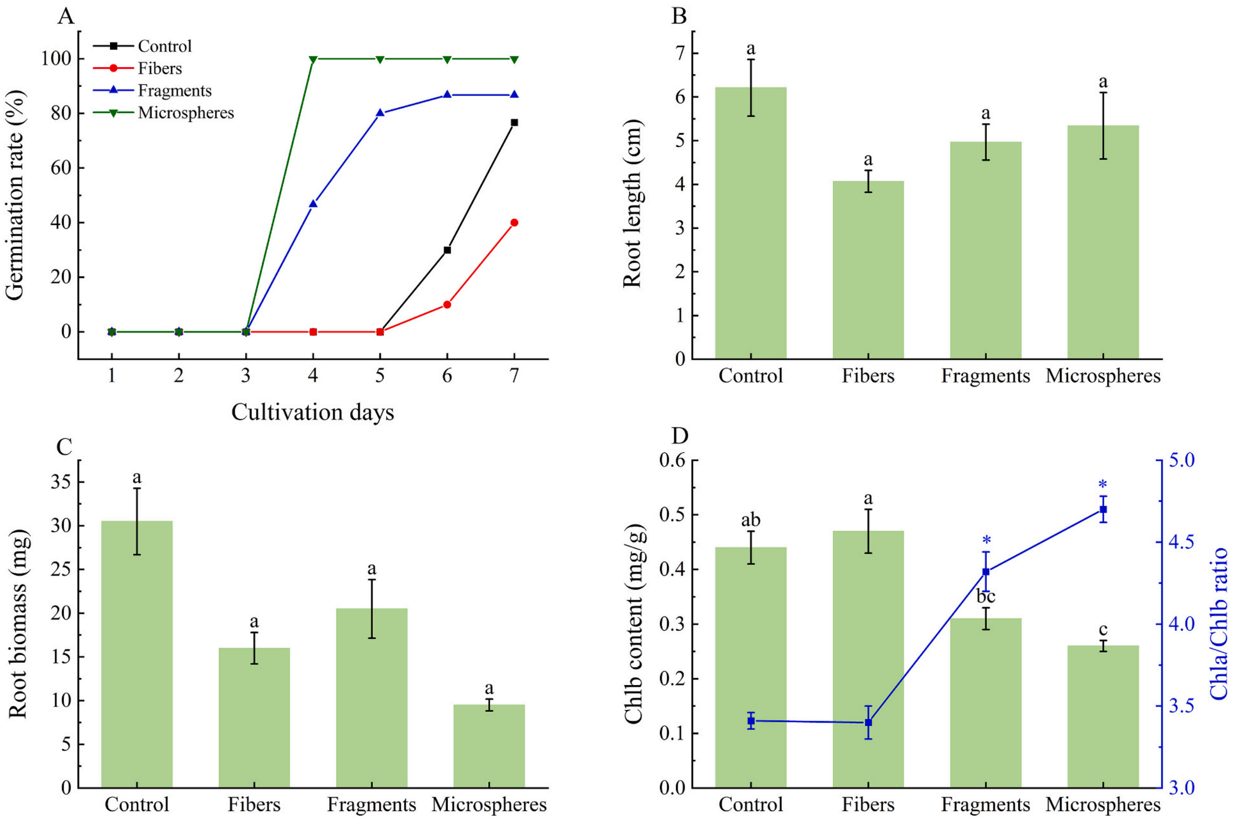


Fig. 2. Effects of various MP exposure on performance parameters in radishes. (A) Germination rate; (B) Root biomass; (C) Root length; (D) Chlb content and Chla/Chlb ratio.

*Letter labels (e.g., a, b, ab): Applied in Duncan's post hoc test to denote specific group differences. Groups sharing the same letter are not significantly different, whereas those with different letters exhibit significant differences.

"*" indicates a statistically significant difference ($p < 0.05$).

with the response mechanism of specific plants to pollutants.

Significant effects on the Chla/Chlb ratio in radish were observed with PET microfragments and PS microspheres compared to the control ($p < 0.05$, Fig. 2D). This suggests that MPs may have a stronger inhibitory effect on the synthesis of Chlb, which is essential for enhancing the efficiency of plant photosynthesis (Boots et al., 2019). Our study confirmed this, showing a significant reduction in Chlb content in radish leaves exposed to PS microspheres ($p < 0.05$, Fig. 2D), with a 40.9 % decrease compared to the control (Table S4). This reduction may result from impaired photosynthesis and nutrient absorption (Li et al., 2021). Additionally, the presence of PS microspheres may cause oxidative damage to plant cells, decreasing the antioxidant capacity of radish leaves. This, in turn, may accelerate the oxidation and degradation of chlorophyll, further impacting its synthesis in radish leaves (Jia et al., 2023).

These results partially confirm our second hypothesis that (ii) MP particles negatively influence plant growth. Specifically, in the early stages, MPs may promote radish germination by altering soil properties such as moisture and temperature due to their intrinsic characteristics. However, in later stages, MPs resulted in declines in various growth parameters, including root length, root biomass, and chlorophyll content. Notably, these changes were closely associated with the types of particles used.

3.4. Effects of PES microfibers on different plants' growth

When evaluating the effects of PES microfibers on different plant species, we observed several interesting findings. First, regarding the germination rate on the seventh day, lettuce achieved a 55.7 % germination rate, significantly higher than the control group's 3.3 % (Fig. 3A). This may be attributed to PES microfibers reducing soil bulk density and increasing soil macroporosity, which enhances water infiltration and improves seed hydration and germination (Ruser et al., 2008; Yu et al., 2023). However, the effects on Chinese cabbage and radish were markedly different, as PES microfibers appeared to delay their germination rates (Fig. 3A). This disparity could be due to varying plant responses to specific PES microfiber characteristics, such as their chemical composition, surface morphology, and structure (Zhang and Liu, 2018). Furthermore, PES microfibers had a beneficial impact on the root growth of certain plants. For instance, exposure to PES microfibers resulted in an increase in lettuce root length by 30.4 % ($p > 0.05$, Fig. 3B and Table S5). Likewise, the root biomass of Chinese cabbage significantly increased by an increase of 57.4 % with the addition of PES microfibers ($p < 0.05$, Fig. 3C and Table S5). This may be related to the influence of microfibers on soil structure or nutrient availability, though further research is needed to explore these mechanisms (Jia et al., 2023). The Chla/Chlb ratio varied significantly among different plant species exposed to PES microfibers ($p < 0.05$, Fig. 3D). However, the presence of PES microfibers increased Chla, Chlb, and total chlorophyll content in radish leaves by 4.7 %, 6.8 %, and 5.2 %, respectively, although these differences were not statistically significant ($p > 0.05$, Table S5). Nonetheless, these findings suggest that PES microfibers may influence photosynthesis and plant growth hormones, though further detailed analysis and experimentation are necessary to determine the concentrations at which these changes become statistically significant. The varied outcomes observed across different plant species, align with our third hypothesis that (iii) the interaction between MP types and plant species exhibits diverse impacts on soil-plant health. These differences could be attributed to species-specific responses and sensitivities to environmental stressors like MPs, which may affect their growth and

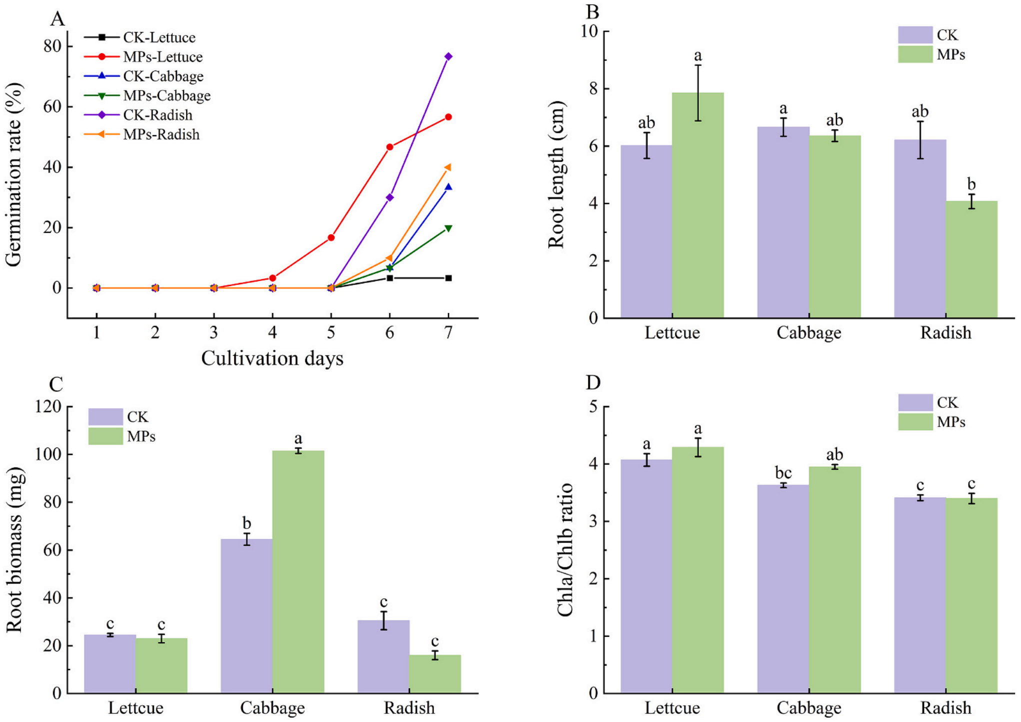


Fig. 3. Effects of PES microfiber exposure on performance parameters in various biological models. (A) Germination rate; (B) Root biomass; (C) Root length; (D) Chla/Chlb ratio.
*CK: The control treatment without the addition of PES microfibers; MPs: The positive treatment with the addition of 100 mg/kg PES microfibers.
*Letter labels (e.g., a, b, ab) are applied in Duncan's post hoc test to denote specific group differences. Groups sharing the same letter are not significantly different, whereas those with different letters exhibit significant differences.

development differently (Gong et al., 2021).

These findings suggest that, under certain conditions, exposure to MPs may enhance plant performance, aligning with previous studies. For instance, Chen et al. (2022) observed increased rice yields when exposed to MPs. Such positive growth responses to MP pollution indicate that MPs could potentially play a role in future agricultural management strategies aimed at improving crop yields. Additionally, MPs may reduce the absorption of soil pollutants by plants, contributing to ecosystem health. Xu et al. (2021) reported that MPs inhibited the uptake of phenanthrene (Phe) by soybean roots, which may be due to MPs adhering to root surfaces and blocking cellular transport pathways for pollutants (Jiang et al., 2019). Moreover, certain types of MPs, such as foams, fragments, and plastic films, have been shown to accelerate soil aeration, thereby increasing soil evaporation rates (Lozano and Rillig, 2020; Wan et al., 2019). Reduced soil moisture has been linked to decreased populations of plant-associated fungal pathogens and harmful soil microbiota, offering potential benefits for plant growth (Lozano et al., 2021). Although this trend was not observed in our study, likely due to the enclosed system limiting water evaporation, further investigations in open-field agricultural settings are needed.

While the short-term benefits of MP exposure warrant attention, the long-term effects on food security and agricultural sustainability remain uncertain. Prolonged exposure to MPs may negatively impact essential ecosystem functions, such as nutrient cycling, soil fertility, and water retention, all of which are critical for sustainable agriculture (Zhou et al., 2024). As observed in our study, as MPs alter soil properties and health, this could lead to reduced root biomass and lower chlorophyll content. Over extended periods, the disruption of soil structure, shifts in microbial communities, the potential accumulation of harmful contaminants on MP surfaces, and the synergistic effects of alien species invasion and MP residues could further deteriorate crop health and soil ecosystems (Zhao et al., 2022). Understanding these long-term risks is crucial, as they may outweigh the short-term benefits, posing significant challenges to agricultural productivity and ecosystem resilience. Further research is needed to fully assess the balance between these short-term gains and potential long-term costs to sustainable agricultural practices.

4. Conclusion

Our study investigated the impact of MPs on soil properties and plant performance, revealing that these effects are multifaceted and vary significantly among particle types and plant species. The observed alterations in key endpoints may result from individual factors or their synergistic interactions. These effects should be viewed holistically, acknowledging that MPs can exert positive, negative, or neutral impacts on soil-plant systems. For instance, while MPs were found to enhance soil moisture retention, this benefit could also promote pathogen activity, potentially inhibiting root growth. Additionally, the presence of MPs improved soil aeration by reducing bulk density, which in turn facilitated plant germination. However, their physical blocking effect may hinder the uptake of essential nutrients and water, leading to reduced root length and biomass. Moreover, MPs may have broader implications for soil-plant systems, particularly concerning SOC stocks and microclimate regulation, given their widespread presence. The unique polymer structures of MPs might also influence biogeochemical processes, potentially contributing to the production of GHGs. This highlights the intricate role that MPs play in terrestrial ecosystems, which are closely tied to food security, human health, and global environmental change. Importantly, the long-term effects of MPs on ecosystem services are still uncertain and warrant further investigation. Future research should focus on their potential impacts on soil health, nutrient cycling, and carbon storage—key components of ecosystem services. Additionally, understanding how MP pollution affects agricultural sustainability is crucial, as it could inform strategies to maintain food production while preserving environmental resilience. Addressing these uncertainties is essential for developing sustainable land management practices amid rising plastic pollution.

CRediT authorship contribution statement

Zhangling Chen: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Laura J. Carter:** Writing – review & editing, Supervision. **Steven A. Banwart:** Supervision, Funding acquisition. **Devlina Das Pramanik:** Software, Methodology. **Paul Kay:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to thank the School of Earth and Environment at the University of Leeds for providing experimental funding for this research. They also extend their gratitude to the Laboratory of the School of Geography (including) Rachel Gasior, David Ashley, Joshua Greenwood, and Holly Armitage, and the Bio-imaging and Flow Cytometry Facility (including) Ruth Hughes and Sally Boxall, at the University of Leeds for their technical support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176641.

References

Bais, H.P., Weir, T.L., Perry, L.G., Gilroy, S., Vivanco, J.M., 2006. Role of root exudates in rhizosphere interactions with plants and other organisms. Annu. Rev. Plant Biol. 57 (1), 233–266. https://doi.org/10.1146/annurev.arplant.57.032905.105159.

Boots, B., Russell, C.W., Green, D.S., 2019. Effects of microplastics in soil ecosystems: above and below ground. Environ. Sci. Technol. 53 (19), 11496–11506. https://doi.org/10.1021/acs.est.9b03304.

Bosker, T., Bouwman, L.J., Brun, N.R., Behrens, P., Vijver, M.G., 2019. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. Chemosphere 226, 774–781. https://doi.org/10.1016/j.chemosphere.2019.03.163.

Botyanszká, L., Šurda, P., Vitková, J., Lichner, Ľ., Igaz, D., 2022. Effect of microplastics on silty loam soil properties and radish growth. Journal of Hydrology and Hydromechanics 70 (3), 321–329. https://doi.org/10.2478/johh-2022-0018.

Chae, An, Y.-J., 2020. Nanoplastic ingestion induces behavioral disorders in terrestrial snails: trophic transfer effects via vascular plants. Environ. Sci. Nano 7 (3), 975–983. https://doi.org/10.1039/C9EN01335K.

Chen, H., Wang, Y., Sun, X., Peng, Y., Xiao, L., 2020. Mixing effect of polylactic acid microplastic and straw residue on soil property and ecological function. Chemosphere 243, 125271. https://doi.org/10.1016/j.chemosphere.2019.125271.

Chen, S., Feng, Y., Han, L., Li, D., Feng, Y., Jeyakumar, P., Sun, H., Shi, W., Wang, H., 2022. Responses of rice (Oryza sativa L.) plant growth, grain yield and quality, and soil properties to the microplastic occurrence in paddy soil. J. Soils Sediments 22 (8), 2174–2183. https://doi.org/10.1007/s11368-022-03232-w.

De Falco, F., Di Pace, E., Cocca, M., Avella, M., 2019. The contribution of washing processes of synthetic clothes to microplastic pollution. Sci. Rep. 9 (1), 6633. https://doi.org/10.1038/s41598-019-43023-x.

de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M. C., 2018. Impacts of microplastics on the soil biophysical environment. Environ. Sci. Technol. 52 (17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Görlich, A.S., Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. Environ. Sci. Technol. 53 (10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104 (1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.

Gao, F., Li, J., Sun, C., Zhang, L., Jiang, F., Cao, W., Zheng, L., 2019. Study on the capability and characteristics of heavy metals enriched on microplastics in marine environment. Mar. Pollut. Bull. 144, 61–67. https://doi.org/10.1016/j.marpolbul.2019.04.039.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7). https://doi.org/10.1126/sciadv.1700782 (e1700782–e1700782).

Gong, W., Zhang, W., Jiang, M., Li, S., Liang, G., Bu, Q., Xu, L., Zhu, H., Lu, A., 2021. Species-dependent response of food crops to polystyrene nanoplastics and microplastics. Sci. Total Environ. 796, 148750. https://doi.org/10.1016/j.scitotenv.2021.148750.

Hallett, P.D., Feeney, D.S., Bengough, A.G., Rillig, M.C., Scrimgeour, C.M., Young, I.M., 2009. Disentangling the impact of AM fungi versus roots on soil structure and water transport. Plant Soil 314 (1–2), 183–196. https://doi.org/10.1007/s11104-008-9717-y.

He, D., Luo, Y., Lu, S., Liu, M., Song, Y., Lei, L., 2018. Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC, Trends in Analytical Chemistry (Regular Ed.) 109, 163–172. https://doi.org/10.1016/j.trac.2018.10.006.

He, D., Zhang, Y., Gao, W., 2021. Micro(nano)plastic contaminations from soils to plants: human food risks. Curr. Opin. Food Sci. 41, 116–121. https://doi.org/10.1016/j.cofs.2021.04.001.

Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190.

Huang, Y., Liu, Q., Jia, W., Yan, C., Wang, J., 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution (1987) 260, 114096. https://doi.org/10.1016/j.envpol.2020.114096.

Ingraffia, R., Amato, G., Iovino, M., Rillig, M.C., Giambalvo, D., Frenda, A.S., 2022a. Polyester microplastic fibers in soil increase nitrogen loss via leaching and decrease plant biomass production and N uptake. Environ. Res. Lett. 17 (5). https://doi.org/10.1088/1748-9326/ac652d.

Ingraffia, R., Amato, G., Bagarello, V., Carollo, F.G., Giambalvo, D., Iovino, M., Lehmann, A., Rillig, M.C., Frenda, A.S., 2022b. Polyester microplastic fibers affect soil physical properties and erosion as a function of soil type. Soil 8 (1), 421–435. https://doi.org/10.5194/soil-8-421-2022.

Iqbal, B., Javed, Q., Khan, I., Tariq, M., Ahmad, N., Elansary, H.O., Jalal, A., Li, G., Du, D., 2023a. Influence of soil microplastic contamination and cadmium toxicity on the growth, physiology, and root growth traits of Triticum aestivum L. S. Afr. J. Bot. 160, 369–375. https://doi.org/10.1016/j.sajb.2023.07.025.

Iqbal, B., Zhao, T., Yin, W., Zhao, X., Xie, Q., Khan, K.Y., Zhao, X., Nazar, M., Li, G., Du, D., 2023b. Impacts of soil microplastics on crops: a review. Applied Soil Ecology: A Section of Agriculture, Ecosystems & Environment 181, 104680. https://doi.org/10.1016/j.apsoil.2022.104680.

Iqbal, B., Zhao, X., Khan, K.Y., Javed, Q., Nazar, M., Khan, I., Zhao, X., Li, G., Du, D., 2024. Microplastics meet invasive plants: unraveling the ecological hazards to agroecosystems. Sci. Total Environ. 906, 167756. https://doi.org/10.1016/j.scitotenv.2023.167756.

Jeffrey, S.W., Humphrey, G.F., 1975. New spectrophotometric equations for determining chlorophyll a, b, c1 and c2 in higher plants and natural phytoplankton. Biochem. Physiol. Pflanz. 167 (2), 191–194. https://doi.org/10.1016/S0015-3796(17)30778-3.

Jia, L., Liu, L., Zhang, Y., Fu, W., Liu, X., Wang, Q., Tanveer, M., Huang, L., 2023. Microplastic stress in plants: effects on plant growth and their remediations. Front. Plant Sci. 14, 1226484. https://doi.org/10.3389/fpls.2023.1226484.

Jiang, T., Ma, X., Tang, Q., Yang, J., Li, G., Schuchardt, F., 2016. Combined use of nitrification inhibitor and struvite crystallization to reduce the NH3 and N2O emissions during composting. Bioresour. Technol. 217, 210–218. https://doi.org/10.1016/j.biortech.2016.01.089.

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobučar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. Environ. Pollut. 1987 (250), 831–838. https://doi.org/10.1016/j.envpol.2019.04.055.

Kalčíková, G., Žgajnar Gotvajn, A., Kladnik, A., Jemec, A., 2017. Impact of polyethylene microbeads on the floating freshwater plant duckweed Lemna minor. Environ. Pollut. 1987 (230), 1108–1115. https://doi.org/10.1016/j.envpol.2017.07.050.

Khalid, N., Aqeel, M., Noman, A., 2020. Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environmental Pollution (1987) 267, 115653. https://doi.org/10.1016/j.envpol.2020.115653.

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature (London) 528 (7580), 60–68. https://doi.org/10.1038/nature16069.

Li, K., Ma, D., Wu, J., Chai, C., Shi, Y., 2016. Distribution of phthalate esters in agricultural soil with plastic film mulching in Shandong Peninsula, East China. Chemosphere 164, 314–321. https://doi.org/10.1016/j.chemosphere.2016.08.068.

Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W.J.G.M., Yin, N., Yang, J., Tu, C., Zhang, Y., 2020. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nature Sustainability 3 (11), 929–937. https://doi.org/10.1038/s41893-020-0567-9.

Li, Y., Liu, X., Shinde, S., Wang, J., Zhang, P., 2021. Impacts of micro- and nanoplastics on photosynthesis activities of photoautotrophs: a mini-review. Front. Microbiol. 12, 773226. https://doi.org/10.3389/fmicb.2021.773226.

Lian, J., Wu, J., Xiong, H., Zeb, A., Yang, T., Su, X., Su, L., Liu, W., 2020. Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (Triticum aestivum L.). J. Hazard. Mater. 385, 121620. https://doi.org/10.1016/j.jhazmat.2019.121620.

Liu, E.K., He, W.Q., Yan, C.R., 2014. "White revolution" to 'white pollution'-agricultural plastic film mulch in China. Environ. Res. Lett. 9 (9). https://doi.org/10.1088/1748-9326/9/9/091001.

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., Li, D., 2019. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci. Total Environ. 675, 462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110.

Lozano, Y.M., Rillig, M.C., 2020. Effects of microplastic fibers and drought on plant communities. Environ. Sci. Technol. 54 (10), 6166–6173. https://doi.org/10.1021/acs.est.0c01051.

Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A., Rillig, M.C., 2021. Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. Front. Plant Sci. 12, 616645. https://doi.org/10.3389/fpls.2021.616645.

Ma, X., Geiser-Lee, J., Deng, Y., Kolmakov, A., 2010. Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci. Total Environ. 408 (16), 3053–3061. https://doi.org/10.1016/j.scitotenv.2010.03.031.

Maes, T., Jessop, R., Wellner, N., Haupt, K., Mayes, A.G., 2017. A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Sci. Rep. 7 (1). https://doi.org/10.1038/srep44501 (44501–44501).

Mahon, A.M., O'Connell, B., Healy, M.G., O'Connor, I., Officer, R., Nash, R., Morrison, L., 2017. Microplastics in sewage sludge: effects of treatment. Environ. Sci. Technol. 51 (2), 810–818. https://doi.org/10.1021/acs.est.6b04048.

Meng, F., Yang, X., Riksen, M., Xu, M., Geissen, V., 2021. Response of common bean (Phaseolus vulgaris L.) growth to soil contaminated with microplastics. Sci. Total Environ. 755 (Pt 2), 142516. https://doi.org/10.1016/j.scitotenv.2020.142516.

Miralles, P., Church, T.L., Harris, A.T., 2012. Toxicity, uptake, and translocation of engineered nanomaterials in vascular plants. Environ. Sci. Technol. 46 (17), 9224–9239. https://doi.org/10.1021/es202995d.

Nizzetto, Bussi, G., Futter, M.N., Butterfield, D., Whitehead, P.G., 2016. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science-Processes & Impacts 18 (8), 1050–1059. https://doi.org/10.1039/C6EM00206D.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S., 2016. Greenhouse gas emissions from soils—a review. Chem. Erde 76 (3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002.

Qi, Y., Yang, X., Pelaez, A.M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (Triticum aestivum) growth. Sci. Total Environ. 645, 1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229.

Ren, X., Tang, J., Wang, L., Liu, Q., 2021. Microplastics in soil-plant system: effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. Plant Soil 462 (1–2), 561–576. https://doi.org/10.1007/s11104-021-04869-1.

Rico, C.M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2011. Interaction of nanoparticles with edible plants and their possible implications in the food chain. J. Agric. Food Chem. 59 (8), 3485–3498. https://doi.org/10.1021/jf104517j.

Rillig, M.C., 2018. Microplastic disguising as soil carbon storage. Environ. Sci. Technol. 52 (11), 6079–6080. https://doi.org/10.1021/acs.est.8b02338.

Rillig, M.C., Ingraffia, R., de Souza Machado, A.A., 2017. Microplastic incorporation into soil in agroecosystems. Front. Plant Sci. 8, 1805. https://doi.org/10.3389/fpls.2017.01805.

Rillig, M.C., de Souza Machado, A.A., Lehmann, A., Klümper, U., 2019a. Evolutionary implications of microplastics for soil biota. Environ. Chem. 16 (1), 3–7. https://doi.org/10.1071/EN18118.

Rillig, M.C., Lehmann, A., de Souza Machado, A.A., Yang, G., 2019b. Microplastic effects on plants. New Phytol. 223 (3), 1066–1070. https://doi.org/10.1111/nph.15794.

Romera-Castillo, C., Pinto, M., Langer, T.M., Álvarez-Salgado, X.A., Herndl, G.J., 2018. Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean. Nat. Commun. 9 (1), 1430–1437. https://doi.org/10.1038/s41467-018-03798-5.

Ruser, R., Sehy, U., Weber, A., Gutser, R., Munch, J.C., 2008. Main driving variables and effect of soil management on climate or ecosystem-relevant trace gas fluxes from fields of the FAM. Perspectives for Agroecosystem Management 2 (2), 79–120. https://doi.org/10.1016/B978-044451905-4.50006-4.

Shim, W.J., Hong, S.H., Eo, S., 2016. Identification methods in microplastic analysis: a review. Anal. Methods 9 (9), 1384–1391. https://doi.org/10.1039/C6AY02558G.

Shim, W.J., Hong, S.H., Eo, S., 2018. Marine microplastics: abundance, distribution, and composition. Microplastic Contamination in Aquatic Environments 1-26. https://doi.org/10.1016/B978-0-12-813747-5.00001-1.

Statista, 2024a. Annual production of plastics worldwide from 1950 to 2022. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/. (Accessed 6 September 2024).

Statista, 2024b. Production forecast of thermoplastics worldwide from 2025 to 2050. https://www.statista.com/statistics/664906/plastics-production-volume-forecast-worldwide/. (Accessed 6 September 2024).

Sun, Y., Ren, X., Pan, J., Zhang, Z., Tsui, T.-H., Luo, L., Wang, Q., 2020. Effect of microplastics on greenhouse gas and ammonia emissions during aerobic composting. Sci. Total Environ. 737. https://doi.org/10.1016/j.scitotenv.2020.139856 (139856–139856).

Tang, Y., Li, G., Iqbal, B., Tariq, M., Rehman, A., Khan, I., Du, D., 2023. Soil nutrient levels regulate the effect of soil microplastic contamination on microbial element metabolism and carbon use efficiency. Ecotoxicol. Environ. Saf. 267. https://doi.org/10.1016/j.ecoenv.2023.115640 (115640–115640).

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, Anthony W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science (American Association for the Advancement of Science) 304 (5672), 838. https://doi.org/10.1126/science.1094559.

Wan, Y., Wu, C., Xue, Q., Hui, X., 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci. Total Environ. 654, 576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123.

Wang, F., Zhang, X., Zhang, S., Zhang, S., Adams, C.A., Sun, Y., 2020. Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation. Toxics (Basel) 8 (2), 36. https://doi.org/10.3390/toxics8020036.

Wang, Z., Li, J., Qu, Z., Ayurzana, B., Zhao, G., Li, W., 2024. Effects of microplastics on the pore structure and connectivity with different soil textures: based on CT scanning. Environ. Technol. Innov. 36, 103791. https://doi.org/10.1016/j.eti.2024.103791.

Xiang, Y., Peñuelas, J., Sardans, J., Liu, Y., Yao, B., Li, Y., 2023. Effects of microplastics exposure on soil inorganic nitrogen: a comprehensive synthesis. J. Hazard. Mater. 460, 132514. https://doi.org/10.1016/j.jhazmat.2023.132514.

Xiang, Y., Rillig, M.C., Peñuelas, J., Sardans, J., Liu, Y., Yao, B., Li, Y., 2024. Global responses of soil carbon dynamics to microplastic exposure: a data synthesis of laboratory studies. Environ. Sci. Technol. 58 (13), 5821–5831. https://doi.org/10.1021/acs.est.3c06177.

Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., Wang, H., Lu, Z., Brookes, P.C., Tang, C., Gan, J., Xu, J., 2020. Microplastics in the soil environment: occurrence, risks, interactions and fate - a review. Crit. Rev. Environ. Sci. Technol. 50 (21), 2175–2222. https://doi.org/10.1080/10643389.2019.1694822.

Xu, G., Liu, Y., Yu, Y., 2021. Effects of polystyrene microplastics on uptake and toxicity of phenanthrene in soybean. Sci. Total Environ. 783, 147016. https://doi.org/10.1016/j.scitotenv.2021.147016.

Yang, M., Huang, D.-Y., Tian, Y.-B., Zhu, Q.-H., Zhang, Q., Zhu, H.-H., Xu, C., 2021. Influences of different source microplastics with different particle sizes and application rates on soil properties and growth of Chinese cabbage (Brassica chinensis L.). Ecotoxicol. Environ. Saf. 222. https://doi.org/10.1016/j.ecoenv.2021.112480 (112480–112480).

Yu, Y., Battu, A.K., Varga, T., Denny, A.C., Zahid, T.M., Chowdhury, I., Flury, M., 2023. Minimal impacts of microplastics on soil physical properties under environmentally relevant concentrations. Environ. Sci. Technol. 57 (13), 5296–5304. https://doi.org/10.1021/acs.est.2c09822.

Zang, H., Zhou, J., Marshall, M.R., Chadwick, D.R., Wen, Y., Jones, D.L., 2020. Microplastics in the agroecosystem: are they an emerging threat to the plant-soil system? Soil Biol. Biochem. 148, 107926. https://doi.org/10.1016/j.soilbio.2020.107926.

Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci. Total Environ. 642, 12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004.

Zhang, G.S., Zhang, F.X., Li, X.T., 2019. Effects of polyester microfibers on soil physical properties: perception from a field and a pot experiment. Sci. Total Environ. 670, 1–7. https://doi.org/10.1016/j.scitotenv.2019.03.149.

Zhang, Z., Cui, Q., Chen, L., Zhu, X., Zhao, S., Duan, C., Zhang, X., Song, D., Fang, L., 2022. A critical review of microplastics in the soil-plant system: distribution, uptake, phytotoxicity and prevention. J. Hazard. Mater. 424 (Pt D). https://doi.org/10.1016/j.jhazmat.2021.127750 (127750–127750).

Zhao, T., Lozano, Y.M., Rillig, M.C., 2021. Microplastics increase soil pH and decrease microbial activities as a function of microplastic shape, polymer type, and exposure time. Front. Environ. Sci. 9, 675803. https://doi.org/10.3389/fenvs.2021.675803.

Zhao, X., Xie, H., Zhao, X., Zhang, J., Li, Z., Yin, W., Yuan, A., Zhou, H., Manan, S., Nazar, M., Iqbal, B., Li, G., Du, D., 2022. Combined inhibitory effect of Canada goldenrod invasion and soil microplastics on rice growth. Int. J. Environ. Res. Public Health 19 (19), 11947. https://doi.org/10.3390/ijerph191911947.

Zhou, J., Zang, H., Loeppmann, S., Gube, M., Kuzyakov, Y., Pausch, J., 2020. Arbuscular mycorrhiza enhances rhizodeposition and reduces the rhizosphere priming effect on the decomposition of soil organic matter. Soil Biol. Biochem. 140, 107641. https://doi.org/10.1016/j.soilbio.2019.107641.

Zhou, C.-Q., Lu, C.-H., Mai, L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y., 2021a. Response of rice (Oryza sativa L.) roots to nanoplastic treatment at seedling stage. J. Hazard. Mater. 401, 123412. https://doi.org/10.1016/j.jhazmat.2020.123412.

Zhou, J., Wen, Y., Marshall, M.R., Zhao, J., Gui, H., Yang, Y., Zeng, Z., Jones, D.L., Zang, H., 2021b. Microplastics as an emerging threat to plant and soil health in agroecosystems. Sci. Total Environ. 787, 147444. https://doi.org/10.1016/j.scitotenv.2021.147444.

Zhou, J., Xu, H., Xiang, Y., Wu, J., 2024. Effects of microplastics pollution on plant and soil phosphorus: a meta-analysis. J. Hazard. Mater. 461. https://doi.org/10.1016/j.jhazmat.2023.132705 (132705–132705).