



Microplastics in Soil Increase Cadmium Toxicity: Implications for Plant Growth and Nutrient Imbalance

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Abstract The increasing presence of microplastics (MPs) and cadmium (Cd) in agricultural soils represents an emerging environmental challenge, necessitating urgent investigation due to their potential synergistic effects on soil and plant health. This study investigated how polyethylene microplastics (PE-MPs) affect Cd behavior in soil, focusing on both their individual and combined impacts on soil pH, Cd bioavailability, plant growth, and nutrient dynamics.

MPs can act as carriers of Cd, enhancing its mobility within the soil–plant system. To achieve this, a pot experiment was conducted using soils treated with different doses of PE MPs (0%, 1%, and 2%, w/w) and Cd (20 mg Cd kg⁻¹). Soil pH, DTPA-extractable Cd, plant growth parameters, Cd accumulation in roots and shoots, and mineral nutrient concentrations were measured. The results indicated that while Cd alone did not significantly alter soil pH, increasing MP doses statistically reduced soil pH and enhanced Cd bioavailability, with DTPA-extractable Cd rising by 14.4% to 25.4%. The combined application of MPs and Cd resulted in a 38% reduction in root yield and a 32% decrease in above-ground biomass. The presence of MPs exacerbated Cd uptake, leading to significantly higher Cd accumulation in both roots and shoots compared to Cd application alone. Moreover, the combined presence of MPs and Cd disrupted the nutrient uptake mechanisms, as evidenced by significant reductions in nitrogen (N) and phosphorus (P) concentrations in root and shoot tissues. These results indicate that MPs and Cd together disrupt soil chemical stability and compromise plant nutritional status. Thus, our findings emphasize that MPs not only serve as physical pollutants but also as vectors that intensify heavy metal contamination risks in agricultural ecosystems.

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1 Introduction

Plastics are extensively used in various sectors of modern life, including the packaging, automotive, electronics, textile, and cosmetics industries, due to their lightweight, flexible nature and high resistance to water and corrosion (Wang et al., 2019). Since the mid-twentieth century, plastics have become an integral part of modern life, with global production reaching 413.8 million tons in 2023 (Plastics Europe, 2024). This widespread use has led to the accumulation of plastic waste in the environment, especially in the form of microplastics (MPs). Microplastics (MPs), defined as particles smaller than 5 mm in diameter, pose a significant threat to both ecosystems and human health. These particles accumulate in soils, damaging plant health and may enter the food chain, ultimately bioaccumulating in humans (Lian et al., 2021; Sun et al., 2021; Yang et al., 2022). Consequently, MPs pollution has emerged as a critical global environmental concern (F. Wang et al., 2022b; Yang et al., 2022).

Recent research has increasingly concentrated on the presence of MPs in agricultural soils, due to concerns regarding potential risks, including their potential to enter the food chain (Medyńska-Juraszek & Szczepańska, 2023). These concerns are further reinforced by the variety of sources through which MPs can be introduced into soil environments. MPs can enter soil from various sources within ecosystems, including atmospheric deposition, contaminated water sources, plastic mulching, coated fertilizers, irrigation practices, flooding, littering, street runoff, and soil amendments like compost and sewage sludge (Allen et al., 2021; Bian et al., 2022; Yadav et al., 2022; B. Zhang et al., 2020a, b). The most common types of plastics detected in soils are polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Liu et al., 2018), with PE frequently reported in concentrations ranging from 9.25 to 369.5 mg PE kg⁻¹ of soil (Li et al., 2020). Given their prevalence, these plastics may affect important ecological and biogeochemical processes in soil systems.

Numerous studies demonstrate that soil microplastics alter physical, chemical, and biological soil properties and negatively affect both plants and microbial communities (Boots et al., 2019; de Souza Machado et al., 2018; F. Wang et al., 2022b). Beyond these direct effects, a major environmental concern is the interaction between MPs and heavy metals,

particularly cadmium (Cd), and alter their fate in the soil–plant system. Microplastics, due to their large specific surface area, act as vectors by adsorbing heavy metals, such as lead (Pb), cadmium (Cd), and zinc (Zn) on their surfaces, thereby facilitating the effective transport of these metals within soil–plant systems (Abbasi et al., 2019, 2020; Chen et al., 2019; Iqbal et al., 2024; Koelmans et al., 2016). Consequently, the interplay between microplastics and heavy metal contamination has emerged as a significant area of focus in contemporary research (Wang et al., 2021; Zeb et al., 2022).

Cadmium, which naturally occurs in soil, has been experiencing a steady annual increase in concentration due to agricultural practices, industrial processes, accidental pollution, and atmospheric deposition, escalating the deterioration of soil quality and posing significant threats to plant health (Alengebawy et al., 2021; Rashid et al., 2023). A study conducted at the Rothamsted Experimental Station in the UK determined that the average Cd input into the soil over a period of 100 years was 3.2 g ha⁻¹ (Alloway & Steinnes, 1999). Moreover, recent findings indicate that MPs may alter Cd dynamics in soil through multiple mechanisms, including altering soil pH, influencing adsorption–desorption dynamics, and facilitating metal leaching and mobility (Huang et al., 2023; S. Zhang et al., 2020a, b). Specifically, polyethylene (PE) MPs have been found to impact Cd bioavailability by serving as adsorption sites for Cd ions, which can subsequently be released under changing environmental conditions, increasing Cd solubility and uptake by plants (Iqbal et al., 2024; Kaur et al., 2022).

The interactions between Cd and MPs significantly influence Cd mobility and toxicity in the soil–plant system. For instance, MPs can influence Cd desorption from soil particles, increasing its availability for plant uptake (Zhang et al., 2023). Furthermore, MPs can disrupt soil microbial communities and enzymatic activities, indirectly affecting Cd solubility and plant nutrient absorption (Huang et al., 2023). Studies on wheat (*Triticum aestivum* L.) indicated that simultaneous exposure to Cd and MPs leads to reduced plant growth, lower biomass, and diminished photosynthetic activity, as well as increased oxidative stress and tissue damage compared to exposure to each pollutant separately (F. Wang et al., 2022a). In another study, a pot experiment was conducted using two different types of microplastics (mPP and mPE),

where increasing doses of MPs (0, 10, 50, 100, 200, 500, 1000, 5000, and 10,000 mg kg⁻¹) and Cd (0, 1, and 5 mg kg⁻¹) were applied to the soil. The results of this study indicated that the combined application of Cd and MPs promoted Cd accumulation in the roots and aerial parts of wheat. Importantly, MPs were shown to intensify Cd uptake in plant tissues, amplifying its phytotoxic effects (Chen et al., 2023). Despite increasing research on MP-heavy metal interactions, studies specifically focusing on the mechanistic pathways through which MPs influence Cd behavior in agricultural systems remain limited. Although studies have examined MP-induced Cd mobilization, little is known about how MPs alter Cd bioavailability, nutrient uptake, and plant health in contaminated soils. Therefore, elucidating the mechanisms underlying these interactions is essential for developing effective mitigation strategies for polluted farmland. This study aims to elucidate how polyethylene MPs influence Cd bioavailability, plant growth, Cd uptake and mineral element concentrations under Cd toxicity conditions.

2 Materials and Methods

The experiment was carried out in a climate-controlled greenhouse during 2024. The greenhouse, equipped with an evaporative cooling system, maintained average nighttime temperatures of 22°C and daytime temperatures of 28°C under natural sunlight.

2.1 Materials

The experimental soil was taken from the top 20 cm of fields at Tokat Gaziosmanpasa University, Faculty of Agriculture in Türkiye. The collected soil was dried at room temperature, ground, and sieved to a 4 mm sieve for pot experiments and to a 2 mm sieve for soil characterization. The soil had a loamy texture, was moderately calcareous (11.6% CaCO₃), with an alkaline pH of 7.83, low in organic matter (1.02%), and was nonsaline (0.14 dS/m). DTPA-extractable Zn, Fe, Mn, Cu, and Cd concentrations were 0.38, 3.32, 6.42, 1.26, and 0.004 mg kg⁻¹, respectively, and no microplastics were detected in the soil.

Basilio bread wheat (*Triticum aestivum* L.) variety was used as the plant material of the experiment. Basilio is an alternative winter wheat cultivar with a

plant height ranging from 80 to 110 cm that produces hard red grains.

Polyethylene (PE) MPs were obtained from a petrochemical company in Ankara, Türkiye. The MPs had a density of 0.935–0.939 g/cm³, a crystallinity of 80–90%, and a softening point between 120°C and 135°C. To achieve a particle size of approximately 100 µm, the MPs were sieved manually. Prior to use, the MPs were washed with 0.1 mol L⁻¹ HNO₃ and then rinsed thoroughly with deionized water to remove impurities (Wang et al., 2021).

2.2 Methods

2.2.1 Experimental Set-Up and Procedure

The experiment was conducted in a completely randomized design (CRD) with three replications. Cadmium treatments were applied at 0 and 20 mg Cd kg⁻¹ (Ali et al., 2022) soil using 3CdSO₄·8H₂O, while MPs were incorporated at three different rates (0%, 1.0%, and 2.0% w/w), and thoroughly mixed with the soil. The microplastic (MPs) doses used in the study were determined by taking into account the information obtained about the presence of microplastics in the soil and previous research (Wang et al., 2021; Wang et al., 2020b; Y. Zhang et al., 2022a, b). Before potting, the soil was pre-treated with basal applications of nitrogen (250 mg kg⁻¹ soil as Ca(NO₃)₂·4H₂O), phosphorus (100 mg kg⁻¹ soil as KH₂PO₄), iron (2.0 mg kg⁻¹ soil as Fe-EDTA), and zinc (2.0 mg kg⁻¹ soil as ZnSO₄·7H₂O), to ensure a uniform nutrient distribution. The soil samples were allowed to equilibrate at room temperature for one week before sowing (Wang et al., 2020a). Fifteen surface-sterilized wheat seeds (2% NaClO, 10 min) were sown per pot (220 × 180 mm, 3 L, 2.75 kg air-dry soil). Once the plants developed two leaves (~5–8 cm in height), thinning was performed to retain seven plants per pot, and they were subsequently irrigated daily with distilled water to maintain 70% of the field capacity moisture content. After 63 days of growth under greenhouse conditions, the plants were harvested when significant growth differences were observed. A 50 g soil sample was collected from each pot after thorough mixing to analyze the pH of the soil and the concentration of available Cd.

2.3 Plant and Soil Analysis

The oven-dry weight (DW) of shoots and roots was measured and reported as grams of dry weight per plant. Roots were first washed with 1 mM CaCl₂ and 1 mM EDTA solutions (Cakmak et al., 2009), and then rinsed with distilled water before drying at 70°C. Shoots were washed with distilled water and 0.5 M hydrochloric acid (HCl) before drying at 70°C. Shoots and roots were digested using a microwave oven (Mars 6, CEM, Matthews, NC) with 2 ml of 35% hydrogen peroxide (H₂O₂) and 5 ml of 65% nitric acid (HNO₃). Digested samples were analyzed for Cd, P, K, Mg, Fe, Zn, Cu, and Mn by an inductively coupled plasma optical emission spectrometer (ICP-OES) (Varian Vista Pro) (Bataglia et al., 1983). Nitrogen concentrations in plant roots and shoots were determined using a Thermo Scientific FlashSmart C/N Analyzer. To ensure accuracy of the measurements, calibration was performed using certified standard reference materials (SRM Number 1573a) from the National Institute of Standards and Technology (NIST, Gaithersburg, MD).

Particle size distribution of soil samples was determined using the hydrometer method (Bouyoucos, 1962). Soil acidity and salinity were assessed by measuring soil pH and electrical conductivity (EC) in a saturated paste extract (Rhoades, 1982). Soil organic matter content was quantified using the modified Walkley–Black method, which is an adaptation of the original Walkley and Black (1934) method (Nelson & Sommers, 1996). Calcium carbonate (CaCO₃) content was determined using a calcimeter (Allison & Moodie, 1965). Bioavailability of Cd, Zn, Fe, Mn, and Cu in the soil was assessed using the sequential extraction procedure of Lindsay and Norvell (1978).

2.4 Statistical Analysis

The study aimed to evaluate the impact of varying levels of Cd and MPs on plant growth and nutrient accumulation in wheat. A two-way analysis of variance (ANOVA) was conducted to assess the individual and interactive effects of Cd and MPs on DW and N, P, K, Cd, Mg, Fe, Zn, Cu, and Mn concentrations in both roots and shoots. Tukey's Honestly Significant Difference (HSD) test ($\alpha = 0.05$) was used to compare means using RStudio (Abdi & Williams, 2010). Normality and homogeneity of variances were

assessed using Q-Q plots, Shapiro–Wilk and Levene's tests. Data transformations were applied when necessary to ensure normality and homogeneity of variance. This statistical approach was also used to evaluate the effects of Cd and MPs on soil properties, including pH and DTPA-extractable Cd, Fe, and Zn concentrations.

3 Results and Discussion

3.1 Soil pH and DTPA-Extractable Cd, Zn, Fe Concentrations

Soil pH plays a critical role in regulating the availability of essential plant nutrients and heavy metals (Gunal et al., 2021). In this study, Cd alone had a negligible impact on soil pH (Table 1), increasing MP doses led to a significant decrease ($P < 0.05$). The highest dose of MPs (MP2) resulted in a significant reduction in pH compared to the control (MP0) and lower dose (MP1). For instance, the initial soil pH of 7.70 decreased to 7.53 and 7.43 with MP1 and MP2 treatments, respectively (Table 1). These findings suggest that microplastic contamination can alter soil chemistry, potentially influencing nutrient dynamics and heavy metal bioavailability (F. Wang et al., 2021, 2022b). The influence of MPs on soil pH is variable, potentially leading to increases, decreases, or no significant change. While many studies have reported

Table 1 Effect of Cadmium and microplastic applications on soil pH and soil DTPA extractable Cd, Zn and Fe concentrations (mg kg⁻¹)

Cd Dose (mg/kg)	MP Dose (%)	pH	Cd	Zn	Fe
Cd0	MP0	7.77 ^c	0.010 ^a	0.91 ^a	15.1 ^c
Cd0	MP1	7.60 ^{abc}	0.013 ^a	0.91 ^a	14.4 ^{bc}
Cd0	MP2	7.47 ^a	0.015 ^a	0.95 ^a	13.9 ^{ab}
Cd20	MP0	7.71 ^{bc}	11.8 ^b	0.96 ^a	14.6 ^{bc}
Cd20	MP1	7.53 ^{ab}	13.5 ^c	1.02 ^a	13.5 ^a
Cd20	MP2	7.43 ^a	14.8 ^d	0.99 ^a	13.4 ^a
Cd Dose		ns	***	ns	***
MP Dose		***	***	ns	***
Cd*MP		ns	***	ns	ns

Means in columns with the same letter do not differ according to Duncan's Multiple

***: $P < 0.001$; ns non-significant

a reduction in soil pH due to MPs (Wang et al., 2021; Yu et al., 2021), Boots et al., (2019) observed a decrease in soil pH after 30-day exposure to 0.1% (w/w) high-density polyethylene (HDPE) MPs. This decrease in soil pH may be attributed to changes in cation exchange dynamics caused by HDPE particles. For instance, Gharahi and Zamani-Ahmadmohammadi (2022) found that high concentrations (5% w/w) of polyethylene terephthalate (PET) MPs significantly decreased soil pH, showing a direct link between MP presence and increased soil acidity. Similarly, Janczak et al., (2020) reported a significant decrease in soil pH due to polylactic acid (PLA) MP contamination.

Increasing doses of MPs application significantly increased DTPA-extractable Cd concentration ($P < 0.05$), except in the Cd0 treatment (Table 1). Under the Cd 20 mg kg⁻¹ treatment, DTPA-extractable Cd increased from 11.8 mg kg⁻¹ in MP0 to 13.5 mg kg⁻¹ (14.4% increase) in the MP1, and 14.8 mg kg⁻¹ (25.4% increase) in the MP2 (Table 1). These findings suggest that MPs enhance the bioavailability of Cd in soil due to their unique surface properties (Wang et al., 2020a; S. Zhang et al., 2020a, b). Unlike hydrophilic soil colloids with abundant functional groups for heavy metal adsorption. Due to their hydrophobic surfaces and limited functional groups, MPs adsorb fewer metals, thereby increasing Cd mobility and bioavailability (Hodson et al., 2017; S. Zhang et al., 2020a, b). These results highlight the potential for MPs to exacerbate heavy metal contamination in agricultural soils, posing risks to plant health and food safety (Jin et al., 2022). S. Zhang et al., (2020a, b) found that the addition of PE MPs increased the desorption of Cd from soil, leading to a higher exchangeable Cd fraction. Wang et al., (2020a) observed that in soil containing 5 mg Cd kg⁻¹, DTPA-extractable Cd concentrations increased with rising PE MP doses (0%, 0.1%, 1%, and 10%). They found that Cd concentrations increased from 3.46 mg kg⁻¹ in the control group (MP0) to 3.82 mg kg⁻¹ at 0.1% MP and 3.81 mg kg⁻¹ at 1% MP. Guo et al., (2023) revealed that MPs, particularly PE and polypropylene (PP), inhibit the chemisorption of Cd²⁺ in soil by blocking active binding sites. This interference prevents the formation of cadmium carbonate (CdCO₃) and cadmium phosphide (Cd₃P₂) precipitates, increasing Cd bioavailability by 1.2 to 1.5 times. This underscores the significant impact of MPs on heavy metal behavior in soil ecosystems.

Cd bioavailability is strongly influenced by soil pH, since lower pH levels increase Cd solubility in water, making it more accessible for plant uptake (Qin et al., 2023). In this study, increasing MP doses led to a decrease in soil pH, which in turn contributed to higher DTPA-extractable Cd concentrations (Table 1). Previous studies have also reported that MPs can lower soil pH. For instance, Huang et al., (2023) observed a slight pH reduction in soils exposed to MPs. These findings align with existing research indicating that lower pH levels are associated with increased Cd concentrations (Argüello et al., 2019).

The effects of Cd and MPs treatments on DTPA-extractable Zn concentrations were not statistically significant (Table 1). However, both Cd and MPs treatments significantly reduced DTPA-extractable Fe concentrations, although their interaction effects were not significant (Table 1). Moreno-Jiménez et al., (2022) found that 0.4% polyester microfibers (PES) MPs increased Zn availability in fertile soil but did not affect Fe, Mn, or Cu availability. Liu et al., (2023) reported that 0% and 2% MP treatments significantly elevated the levels of essential micronutrients, including Zn, Fe, and Mn, especially when combined with Cd at 5 mg kg⁻¹. They suggested that MPs may hinder the adsorption of these micronutrients, increasing their bioavailability.

3.2 Root and Shoot Yields

Independent of MP treatments, Cd exposure significantly reduced both root and shoot dry weights (Fig. 1a and 1b). At the Cd20MP0 dose, root dry matter decreased by 28% from 0.32 g plant⁻¹ to 0.23 g plant⁻¹, while shoot dry matter decreased by 19% from 1.04 g plant⁻¹ to 0.84 g plant⁻¹ (Fig. 1a and 1b). This biomass reduction likely reflects Cd phytotoxicity (Cai et al., 2020). The negative correlation between Cd dose and plant yield is well-documented in the literature (Erdem et al., 2012; Zhou et al., 2020), emphasizing the adverse effects of Cd on plant growth and the imperative need for strategies to alleviate its negative consequences.

Increasing MPs concentrations negatively impacted wheat growth and biomass production, potentially posing risks to agricultural productivity. Regardless of Cd treatment, increasing MPs doses significantly reduced root and shoot dry matter

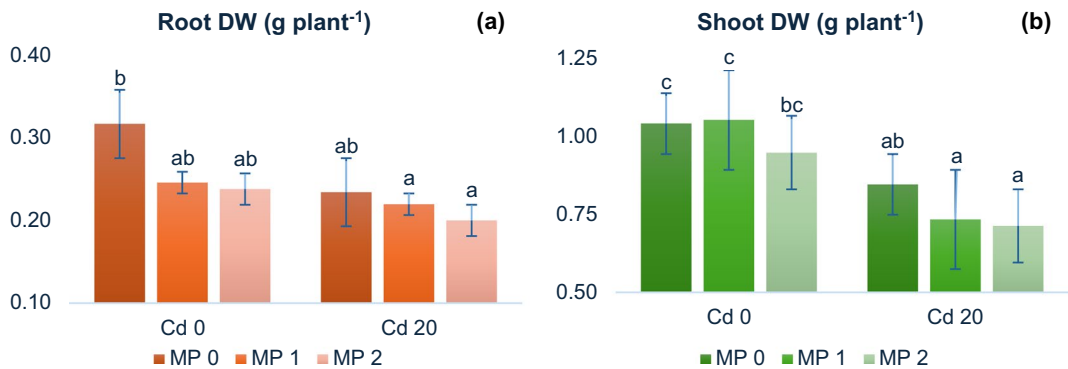


Fig. 1 Effects of Cd and MPs treatments on root and shoot dry weight. Different letters indicate significant differences at ($P < 0.05$)

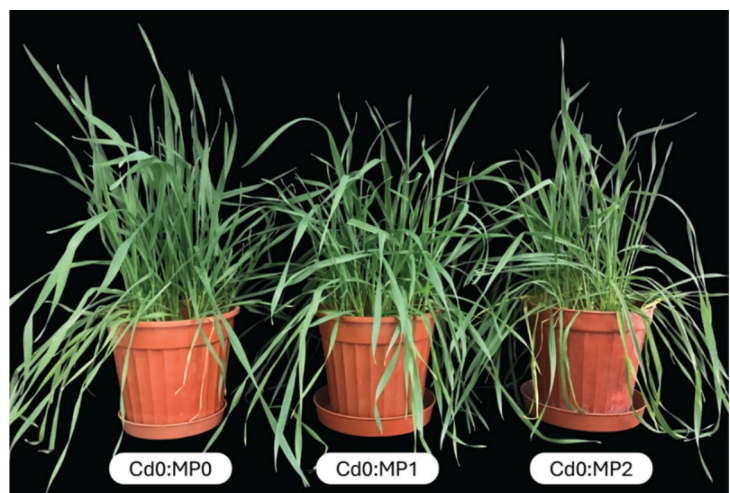
yields ($P < 0.05$) (Figs. 1a and 1b). Root dry matter decreased from $0.32 \text{ g plant}^{-1}$ in the Cd0MP0 treatment to $0.25 \text{ g plant}^{-1}$ (22% reduction) at MP1 and $0.24 \text{ g plant}^{-1}$ (25% reduction) in MP2 (Fig. 1a). Shoot dry matter remained unchanged at $1.05 \text{ g plant}^{-1}$ in MP1 but decreased to $0.95 \text{ g plant}^{-1}$ (8.65% reduction) in MP2 (Fig. 1b and Fig. 2).

Microplastics can directly and indirectly impact plant growth (L. Wang et al., 2022a, b, c). Direct effects include root accumulation, which can hinder shoot development by reducing root elongation, activity, and biomass production (Wang et al., 2023). Indirectly, MPs can impair nutrient and water uptake by altering soil functions (F. Wang et al., 2022b). Research has shown that MPs can significantly reduce yields in various plant species, including wheat (Qi et al., 2018), broad beans (*Vicia faba* L.), and onions

(*Allium cepa* L.) (Lian et al., 2022). Huang et al., (2023) observed an 11.8% reduction in average shoot biomass due to MPs, with a range of 8.51% to 15.0%.

Research has shown that the combination of MPs and Cd in soils negatively impacts plant growth and development (Jia et al., 2022; Zeb et al., 2022). In this study, increasing MPs doses, under Cd toxicity (Cd20) significantly decreased wheat root and shoot dry matter yield (Fig. 1a and 1b). For example, root dry weight decreased from $0.32 \text{ g plant}^{-1}$ in the control (Cd0MP0) to $0.23 \text{ g plant}^{-1}$ (28% reduction) in Cd20MP0 and decreased further to $0.20 \text{ g plant}^{-1}$ (38% reduction) in Cd20MP2 treatments (Fig. 1a). These results show the detrimental effects of Cd and MPs co-contamination on wheat growth and emphasize the need for effective management strategies for contaminated agricultural soils. These findings show

Fig. 2 Effect of increasing doses of MPs applications on plant growth under Cd0 conditions



that combined MP contamination and Cd toxicity significantly impair root growth, causing a marked decrease in root biomass. A comparable reduction in yield was observed in the shoot dry matter of control treatment, which exhibiting a dry matter yield of 1.04 g per plant (Fig. 1b). In the Cd20MP0 treatment, the yield decreased to 0.84 g per plant, representing a 19% reduction. In the Cd20MP2 treatment, the yield decreased further, to 0.71 g per plant, resulting in a 32% reduction (Fig. 1b, Fig. 3).

The research conducted by Li et al., (2024) explored the impacts of PE (0.05% w/w), PLA (0.05% w/w), and Cd (5 mg kg⁻¹ soil) on the growth of Chinese cabbage (Pak Choi) under greenhouse conditions. The findings revealed that the combination of PE and Cd treatments significantly reduced plant growth and biomass yield (both root and shoot). This suggests a synergistic effect between MPs and Cd, exacerbating their inhibitory effects on plant growth.

Overall, these findings align with previous studies indicating that MPs enhance heavy metal bioavailability and decrease plant growth (Iqbal et al., 2023; Wang et al., 2019). The study further suggests that the combined effects of Cd and MPs are more detrimental to plant growth than either contaminant alone, as supported by Huang et al., (2023).

3.3 Root and Shoot Cd Concentrations

The plant-available concentration of Cd is a critical factor influencing plant Cd uptake (Umair et al., 2021). As DTPA-extractable Cd concentrations increase, plant Cd accumulation also increases (Erdem, 2021; Wiesler, 2012). In this study, the

addition of 20 mg kg⁻¹ Cd significantly increased root and shoot Cd concentrations ($P < 0.001$), regardless of MPs treatment (Table 2). In the control treatment, root Cd concentration increased from 0.33 mg kg⁻¹ to 144.6 mg kg⁻¹, and shoot Cd concentration increased from 0.13 mg kg⁻¹ to 21.6 mg kg⁻¹ (Table 1). Melo et al., (2011) studied soybean cultivation in Entisol and Oxisol soils with Cd concentrations up to 10.4 mg kg⁻¹. They found a direct correlation between soil Cd concentration and Cd accumulation in soybean roots and leaves. Higher soil Cd levels resulted in increased plant Cd uptake, indicating the significant impact of soil Cd on plant tissues.

MPs can significantly interact with Cd, enhancing plant Cd uptake from the soil (Wang et al., 2020a, b). Consistent with this, increasing MPs concentrations in the Cd20 treatment led to a significant increase ($P < 0.001$) in root and shoot Cd concentrations (Table 2). For example, root Cd concentration increased from 145 mg kg⁻¹ in the MP0 treatment to 168 mg kg⁻¹ (16% increase) in MP1 and 184 mg kg⁻¹ (27% increase) in MP2 (Table 2). Due to their hydrophobic properties and large specific surface area, MPs can enhance Cd mobility in soils, thereby increasing its bioavailability in the soil–plant system (Wang et al., 2021). These findings are also consistent with the DTPA-extractable Cd concentrations observed with MPs applications (Table 1). Similar to root Cd concentrations, shoot Cd concentrations also increased significantly ($P < 0.001$) with the MPs application (Table 2). In the Cd20 treatment, shoot Cd concentration increased from 21.6 mg kg⁻¹ in MP0 to 29.0 mg kg⁻¹ (34% increase) in MP1 and 34.2 mg kg⁻¹

Fig. 3 Effect of Cd and MP applications on plant growth

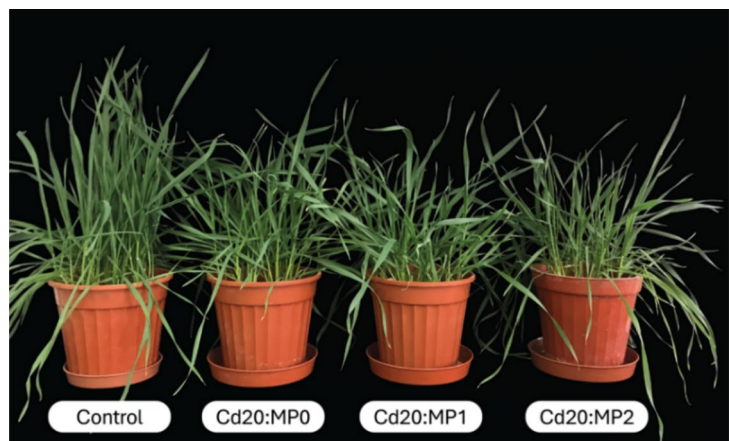


Table 2 Effect of Cd and MP applications on Cd concentration in root and shoot of wheat plant

Cd Dose (mg kg ⁻¹)	MP Dose (%)	Root Cd Concentration (mg kg ⁻¹)	Shoot Cd Concentration (mg kg ⁻¹)
Cd0	MP0	0.33 ^a	0.13 ^a
Cd0	MP1	0.41 ^a	0.12 ^a
Cd0	MP2	0.38 ^a	0.16 ^a
Cd20	MP0	144.6 ^b	21.6 ^b
Cd20	MP1	167.9 ^c	29.0 ^c
Cd20	MP2	183.7 ^d	34.2 ^d
Cd Dose		***	***
MP Dose		***	***
Cd*MP		***	***

Means in columns with the same letter do not differ according to Duncan's Multiple Range test at *P* < 0.05

***: *P* < 0.001; *ns* non-significant

(58% increase) in MP2 (Table 2). These findings align with Huang et al., (2021), who reported that MPs enhance Cd bioavailability in soil, leading to increased Cd bioaccumulation in *Eisenia fetida*.

The 2% MP treatment (MP2) resulted in significantly higher root and shoot Cd concentrations compared to other treatments (Table 2). Previous research has shown that MPs concentration and morphology can influence heavy metal bioavailability. PE MPs, especially at higher concentrations, can enhance Cd bioavailability (Li et al., 2021). These findings are consistent with studies indicating that MPs alter soil chemistry and dynamics by reducing soil pH, which enhances Cd desorption, while simultaneously interacting with dissolved organic matter to modify metal complexation and increase bioavailability (Boots et al., 2019; Yu et al., 2020).

3.4 Root and Shoot Mineral Element Concentrations

The combined exposure to Cd and MPs significantly decreased the concentrations of essential nutrients (N, P, K, Mg) in both roots and shoots (Table 3). For instance, root N content declined from 1.96% in the Cd0MP0 treatment to 1.72% in Cd20MP0 and further to 0.75% in Cd20MP2, indicating a negative impact on nutrient assimilation. The decline in N and P concentrations is likely due to the disruption of root structure and function by Cd and MPs. Heavy metals like Cd can interfere with nutrient uptake and transport (Yang et al., 2020), while MPs can physically obstruct root surfaces, reducing water and nutrient absorption (Huang et al., 2021). These findings align with previous research, suggesting that combined pollution can exacerbate nutrient deficiencies, impairing plant growth and productivity. A similar decline in nutrient concentrations was observed in wheat shoots.

Table 3 Effect of Cd and MP applications on concentrations of N, P, K and Mg in root and shoot of wheat plants

MP Dose (%)	N (%)		P (%)		K (%)		Mg (%)	
	Cd0	Cd20	Cd0	Cd20	Cd0	Cd20	Cd0	Cd20
Root Concentration								
MP0	1.96 ^c	1.72 ^{bc}	0.17 ^c	0.15 ^{bc}	0.71 ^a	0.68 ^a	0.25 ^a	0.29 ^{ab}
MP1	1.51 ^{bc}	1.26 ^{ab}	0.17 ^c	0.12 ^a	0.64 ^a	0.61 ^a	0.24 ^a	0.28 ^{ab}
MP2	1.46 ^{bc}	0.75 ^a	0.15 ^{bc}	0.13 ^{ab}	0.61 ^a	0.72 ^a	0.27 ^{ab}	0.32 ^b
Shoot Concentration								
MP0	4.62 ^b	4.26 ^{ab}	0.32 ^b	0.29 ^{ab}	4.30 ^a	4.74 ^b	0.46 ^{ab}	0.47 ^b
MP1	4.41 ^b	4.21 ^{ab}	0.32 ^b	0.26 ^a	4.44 ^a	4.71 ^b	0.46 ^{ab}	0.44 ^a
MP2	3.87 ^{ab}	3.31 ^a	0.30 ^{ab}	0.26 ^a	4.24 ^a	4.49 ^{ab}	0.46 ^{ab}	0.45 ^a

Means in columns with the same letter do not differ according to Duncan's Multiple Range test at *P* < 0.05

Shoot N concentration decreased from 4.62% in the Cd0MP0 treatment to 4.26% in Cd20MP0 and 3.31% in Cd20MP2, mirroring the increased Cd concentrations in plant tissues (Table 2). This suggests an inverse relationship between Cd uptake and N assimilation. Even in the absence of Cd, increasing MPs doses significantly reduced N concentrations in both roots and shoots, emphasizing the independent impact of MPs on nutrient availability and plant health. For example, the root N concentration decreased from 1.96% to 1.46% and the shoot N concentration decreased from 4.62% to 3.87% with increasing MPs doses (Table 3).

The decrease in N concentrations observed in MPs, Cd, and combined Cd × MP treatments (Table 3) indicates that these contaminants not only have individual toxic effects but also interact to further disrupt nutrient uptake. MPs can negatively impact plant growth not only through direct physical blockage but also by altering soil properties and root function (L. Wang et al., 2022a, b, 2022c). Furthermore, they can accumulate within plant cell wall pores, restricting water and nutrient flow, ultimately reducing uptake efficiency (Z. Zhang et al., 2022a, b).

The presence of MPs heightened plant sensitivity to Cd toxicity, significantly reducing shoot and root N and P concentrations. Cd interferes with the uptake and translocation of essential elements (Ca, Fe, Mg, P, K, Mn, Cu, Zn) and water, disrupting plant physiology (Abedi & Mojiri, 2020; Rucińska-Sobkowiak, 2016). This interference occurs through competition for uptake sites and disruption of cellular transport mechanisms. The combined presence of MPs and Cd intensifies their negative effects on plants by altering soil structure and chemistry, which in turn limits

ion exchange and water retention, leading to nutrient deficiencies that further compromise plant health and biomass production (de Souza Machado et al., 2019; Huang et al., 2023).

The exact mechanisms by which Cd disrupts mineral nutrient uptake and utilization in plants are complex and not fully understood. Cd may affect plasma membrane permeability, interfering with nutrient uptake by altering membrane-bound transport protein activity and specificity (Qin et al., 2020). This disruption can impact key nutrient transporters, leading to imbalances in nutrient availability and composition within plant tissues. Cd is known to impair nitrate (NO_3^-) uptake and its movement from roots to shoots by reducing nitrate reductase activity in shoots (Rizzardo et al., 2012). Additionally, Cd can bind to sulfhydryl groups in proteins, disrupting the structure and function of nutrient transport proteins and enzymes essential for nutrient utilization (Van Assche & Clijsters, 1990). This can interfere with nutrient transport and lead to nutrient displacement, causing macronutrient deficiencies and structural protein damage.

The application of 20 mg kg^{-1} Cd significantly reduced root and shoot Zn concentrations (Table 4). Root Zn concentration decreased from 27.1 mg kg^{-1} in the Cd0MP0 treatment to 21.7 mg kg^{-1} in the Cd20MP0 treatment. A similar trend was observed in shoots. This reduction can be attributed to the antagonistic interaction between Cd and Zn (Erdem et al., 2012; Grant et al., 1998).

Despite the cadmium-induced reduction in Zn concentrations, increasing MPs doses led to a significant increase in root Zn concentrations (Table 4). For example, under Cd20 treatment, root Zn concentration increased from 23.2 mg kg^{-1} in MP0

Table 4 Effect of Cd and MP applications on concentrations of Zn, Fe, Mn and Cu in roots and shoots of wheat plants

MP Dose (%)	Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	Cd0	Cd20	Cd0	Cd20	Cd0	Cd20	Cd0	Cd20
<i>Root Concentration</i>								
MP0	38.8 ^{bc}	23.2 ^a	2677 ^a	2303 ^a	74.5 ^a	68.1 ^a	21.9 ^a	40.1 ^b
MP1	58.1 ^d	31.7 ^{ab}	2406 ^a	1979 ^a	63.5 ^a	54.8 ^a	24.9 ^a	37.2 ^b
MP2	61.2 ^d	45.0 ^c	2836 ^a	2408 ^a	60.7 ^a	61.9 ^a	23.6 ^a	41.1 ^b
<i>Shoot Concentration</i>								
MP0	27.1 ^b	21.7 ^a	64.9 ^{bc}	60.4 ^{ab}	29.5 ^a	38.1 ^{bc}	10.4 ^b	8.3 ^a
MP1	27.9 ^b	20.8 ^a	57.2 ^a	62.8 ^{abc}	30.0 ^a	43.2 ^c	10.8 ^b	8.5 ^a
MP2	29.5 ^b	20.5 ^a	67.1 ^c	61.3 ^{abc}	32.8 ^{ab}	38.9 ^{bc}	10.6 ^b	8.4 ^a

Means in columns with the same letter do not differ according to Duncan's Multiple Range test at $P < 0.05$

to 45.0 mg kg⁻¹ in MP2. This aligns with Bethanis and Golia (2023), who found that PE microplastics (2.5% and 5% doses) increased Zn bioavailability in lettuce, leading to higher root Zn uptake. However, this effect was less consistent in shoots. Bethanis and Golia (2023) found that PE MPs increased Zn concentrations in both lettuce roots and leaves. At 2.5% and 5% PE MPs doses, Zn concentrations increased by 11.5% and 26.6% in roots and 9.1% and 21.1% in leaves, respectively (Bethanis & Golia, 2023). Similarly, our study showed that MPs and Cd applications significantly altered Fe, Mn, and Cu concentrations in wheat roots and shoots (Table 4). These findings align with Dong et al., (2022), who reported decreased iron (Fe) and manganese (Mn) concentrations in rice roots exposed to polystyrene (PS) and polytetrafluoroethylene (PTFE) MPs. Similarly, Colzi et al., (2022) demonstrated that various MPs (PP, PET, PVC, and PE) reduced Fe, Zn, Cu, and Mg concentrations in squash leaves, suggesting that MPs can influence nutrient allocation between roots and shoots.

4 Conclusion

This study investigated the effects of MPs on Cd dynamics in Cd-contaminated soil, focusing on plant Cd accumulation, growth, nutrient uptake, and soil Cd availability. Results indicate that both contaminants, especially in combination, significantly stress plant development. While Cd is a known phytotoxicant that reduces root and shoot yields, MPs exacerbate these effects. The study demonstrated that MPs not only increase Cd bioavailability in soil but also promote higher Cd uptake in plants, aggravating Cd's inhibitory effects on growth.

The MP-induced soil pH decline shows how MPs modify soil chemistry and influence heavy metal speciation and mobility. Specifically, application of 2% polyethylene MPs (MP2) reduced soil pH from 7.77 to 7.43 and increased DTPA-extractable Cd by 25.4%. The combined Cd20MP2 treatment resulted in a 38% reduction in root dry matter and a 32% decrease in shoot biomass compared to the control. Root Cd concentration increased from 144.6 mg kg⁻¹ (Cd20MP0) to 183.7 mg kg⁻¹ (Cd20MP2), while shoot Cd rose from 21.6 mg kg⁻¹ to 34.2 mg kg⁻¹. Phosphorus content in both roots and shoots followed a similar declining trend. Additionally, nitrogen concentrations

in roots declined from 1.96% to 0.75%, and in shoots from 4.62% to 3.31%. This dual effect of MPs, increasing heavy metal uptake and disrupting nutrient assimilation, underscores their significant impact on plant health and productivity.

Mitigating soil pollution on crop productivity requires detailed insight into how MPs and heavy metals jointly affect soil functions and plant physiology. Further research should clarify the mechanisms underlying MPs-Cd interactions and their impacts on soil properties, nutrient cycling, and plant growth. In addition, studies across various soil types and agricultural systems can provide a broader perspective.

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

Declarations

Competing interests The authors declare that they have no competing interests.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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