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# Effect of Polyethylene (LDPE) Microplastic on Remediation of Cadmium Contaminated Soil by *Solanum nigrum* L.

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## Abstract

*Solanum nigrum* L. has a delightful prospect as a hyperaccumulation plant for cadmium pollution remediation, and microplastic is a new type of pollution that has received wide attention. In this study, the effects of polyethylene microplastics (LDPE) (0.135, 0.27, 0.81 and 1.35 mg·kg$^{-1}$) and cadmium (20 mg·kg$^{-1}$) on the growth indexes and soil physical and chemical properties of *Solanum nigrum* L. were investigated in a 17-day microcosm experiment. The results showed that single LDPE contamination showed a trend of low concentration promotion and medium-high concentration inhibited the growth index of *Solanum nigrum* L. and soil physicochemical index, and single Cd contamination was more stressful to plants than single LDPE contamination, while low concentration of LDPE could reduce the effect of Cd on soil physical and chemical properties and promote plant growth and uptake of soil nutrients. These findings suggest that high concentrations of microplastics can inhibit the growth of *Solanum nigrum* L. alone or in combination with Cd, rather than reducing the toxicity of Cd.

## Keywords

Microplastics, Heavy Metal, Compound Pollution, Phytoremediation, *Solanum nigrum* L.

## 1. Introduction

Over 80% of marine plastic waste comes from land-based sources, and it is in the terrestrial biosphere that we regularly see the highest concentrations of plastic waste. Therefore, the long-term accumulation of plastics makes the terrestrial ecosystem a storage site for plastics, which may affect freshwater and marine ecosystem in the coming decades. An important source of plastics in terrestrial ecosystems is agricultural plastics, the global use of plastic more than 6 million tons in 2018. It is estimated that only 6% - 26% of plastic fragments are recycled, while the remainder becomes microplastics (MPs, <5 mm) through physical wear, UV irradiation, thermal oxidation and microbial treatment (Zhou et al., 2021).

MPs can enter agroecosystems through a variety of pathways, including fertilizer spraying, wastewater irrigation, compost addition, and biological compost application, and with the plastic film having the greatest impact. In general, the degradation cycle of microplastics in the soil is very long, and it usually takes hundreds or even thousands of years to fully mineralize. In many countries, plastic particles are more abundant in agricultural soils than in urban soils due to the frequent use of plastic cultivation and slower-rate surface water runoff for irrigation. In China, where plastics are widely used in agricultural ecosystem, the concentration of plastic particles in the soil is usually between 7100 $kg^{-1}$ and 42,900 $kg^{-1}$ (an average of 18,760 $kg^{-1}$ Soil), of which 95% are between 0.05 and 1 mm (i.e. MPS) (Rillig, 2018). As such high concentrations of microplastics are found in agricultural ecosystem, it is critical to assess the impact of microplastics on plant-soil health.

Once microplastic it enters the soil, it can directly or indirectly affect ecosystem function and plant-soil health. Microplastics can alter the physical and chemical properties of soil (pH value, soil aggregate, bulk density and water holding capacity), in turn, it has different effects on microbial functions as well as plant growth indexes. There is growing evidence that microplastics may have an impact on soil physical and chemical properties and plant growth. Anderson et al. found that the addition of microplastics led to the change of soil physical parameters which affected hydrodynamics and microbial activity (de Souza Machado et al., 2019). Li et al., (2021) found that microplastics reduced the adsorption capacity of soil to metals and improved the exchangeable fractionation and bioavailability of metals in soil.

It is generally accepted that toxicity increases with the increase of adsorption capacity of MPs, which depends on the type, size, and shape of MPs. For example, polyamide has a greater affinity for adsorbing antibiotics than polyvinyl chloride, polyethylene and polypropylene which is due to its porous structure and hydrogen bond between the amide group (proton donor group) and antibiotic carbonyl group (proton acceptor group). The particle size of MPs has a greater effect on the toxicity of plant, with smaller particle sizes being more harmful to plants. For example, nano plastics can slow down or completely inhibit the absorption of water and nutrients by adhering to the seed surface and physically blocking stomata (Li et al., 2021). In fact, microplastics may trigger a variety of signaling pathways which can affect cell proliferation/metabolism and genomic function. Further studies are needed to clarify the interaction of microplastics in cells, their role in long-term exposure, and their possible movement from the roots of plants to the aboveground parts (Giorgetti et al., 2020). The contamination of agricultural land by microplastics is an urgent problem to be solved, to the ability of edible plants to take up nanoplastics, which leads to the entry of nano plastics into the food chain.

Cadmium is water-soluble and non-degradable in the environment. Cadmium in soil is easy to be absorbed by crops, resulting in food pollution through the food chain and ultimately endangering human health. Phytoremediation of contaminated soil has the advantages of low cost and easy method, which can be used for cadmium contaminated soil remediation. *Solanum nigrum* L. is a plant which can be super enriched with heavy metal cadmium and can be used in the practice of remediation of heavy metal cadmium pollution in farmland (Li & Xu, 2017; Wei et al., 2005; Yan et al., 2020).

When microplastics and heavy metals coexist, plant roots ingesting microplastics that have adsorbed heavy metals may change the biotoxic effects of heavy metals. Wang et al., 2021 explored the joint toxicity of original PVC microplastics and cadmium to *Vallisneria natans* and found that PVC microplastics can improve the growth inhibition of cadmium on bitter grass. Gu et al., (2021) studied the combined toxicity of aged PVC microplastics and cadmium on wheat and found that aged PVC microplastics and low concentration Cd could synergistically inhibit the growth of wheat roots. There are few reports about the combined toxicity of microplastics and heavy metals to *Solanum nigrum* L.

Therefore, this study evaluated the effects of single cadmium, single LDPE microplastic and LDPE-$Cd^{2+}$ on *Solanum nigrum* L. and soil. The adsorption mechanism between Cd and LDPE microplastics and the combined toxic effect on *Solanum nigrum* L. were analyzed. It provides a theoretical basis for the further study on the combined effect of heavy metals and microplastics on biology.

## 2. Methods

### 2.1. Materials and Methods

The test soil was collected from the cold black soil in Qing'an County, Heilongjiang Province. The basic physical and chemical properties of the soil are shown in **Table 1**. The tested *Solanum nigrum* L. seeds were purchased from Taobao. The microplastic is low density polyethylene (LDPE) with particle size of 150 μm, purchased from Taobao, originated from Singapore. In the pot experiment, flowerpots with a diameter of 15 cm and a height of 10 cm were used for cultivation, and each pot was filled with 500 g of air-dried soil. All the chemical reagents used in the experiment were analytical pure, cadmium chloride, ammonium molybdate, sodium hydroxide, sodium bicarbonate and potassium dihydrogen phosphate.

**Table 1.** Soil physical and chemical properties.

| pH | Organic matter (g·kg$^{-1}$) | Hydrolyzed nitrogen (mg·kg$^{-1}$) | Available phosphorus (mg·kg$^{-1}$) | Cd (mg·kg$^{-1}$) |
|---|---|---|---|---|
| 6.42 | 106.20 | 609.00 | 51.07 | 0.32 |

## 2.2. Test Method

### 2.2.1. Characterization of Microplastics

Fourier transform infrared spectroscopy (FTIR) (Thermo Fisher in 10, USA) potassium bromide tablet technology is used to determine the infrared spectrum of LDPE microplastics in the range of 500 - 4000 cm$^{-1}$ before and after illumination. The experiment adopts 32 scanning times and 4 cm$^{-1}$ resolution. Field emission scanning electron microscopy (SEM, Hitachi s4800, Japan) was used to collect SEM images of microplastics to analyze the morphology and particle size distribution of micro plastics.

### 2.2.2. *Solanum nigrum* L. Toxicity Test

A total of 10 treatments were set up in the experiment, and each treatment was repeated twice. Blank group (CK without LDPE and cadmium), single LDPE group with different amount, cadmium group with fixed concentration (20.00 mg·kg$^{-1}$) and LDPE group with different concentration were set up respectively. Among them, the microplastic concentrations were $A_0$, $A_1$, $A_2$, $A_3$ and $A_4$, which are 0.000, 0.135, 0.270, 0.810 and 1.350 g·kg$^{-1}$ respectively. In the experiment, the amount of microplastic was based on the residue of agricultural film 151 kg·hm$^{-2}$ in the field (Yan et al., 2014), Cadmium in soil was added in the form of solution by dissolving cadmium chloride in water, fully mix it and fill the basin. Each basin is filled with 500 g soil for one week. Day temperature was set at 25˚C, night temperature at 20˚C, and relative humidity at 60%. Each pot was sown with 3 seeds of *Solanum nigrum* L., and the seedling growth and soil moisture were observed daily after the seedlings emerged to ensure sufficient soil moisture, and the soil and plant indexes were measured by destructive sampling at 10 and 17 d after planting.

The determination of soil pH adopts the potentiometric method, the determination of soil organic matter adopts the wet oxidation method, the determination of soil hydrolytic nitrogen adopts the alkali hydrolysis diffusion method, the determination of soil available phosphorus adopts the sodium bicarbonate extraction molybdenum antimony anti colorimetry method, and the determination of soil soluble organic matter adopts the ultraviolet spectrophotometry (National Agricultural Technology Promotion Service Center, 2006). The content of heavy metals in soil was determined by hand-held heavy metal tester.

AS shown in **Figure 1**, the height of *Solanum nigrum* L. and root length of the main roots of were measured with vernier calipers; the roots were washed with tap water, excess water was sucked out with absorbent paper, and the fresh weight of the roots was determined; chlorophyll of fresh *Solanum nigrum* L. leaves was measured with a chlorophyll meter; and the leaf area of *Solanum nigrum* L. was

**Figure 1.** (a) *Solanum nigrum* L. growing under hydroponics, (b) *Solanum nigrum* L. growing under hydroponics, (c) *Solanum nigrum* L. of Solanum on the 10th and 17th days.

determined by the weighing method. The experimental data were analyzed and processed using Origin 2019.

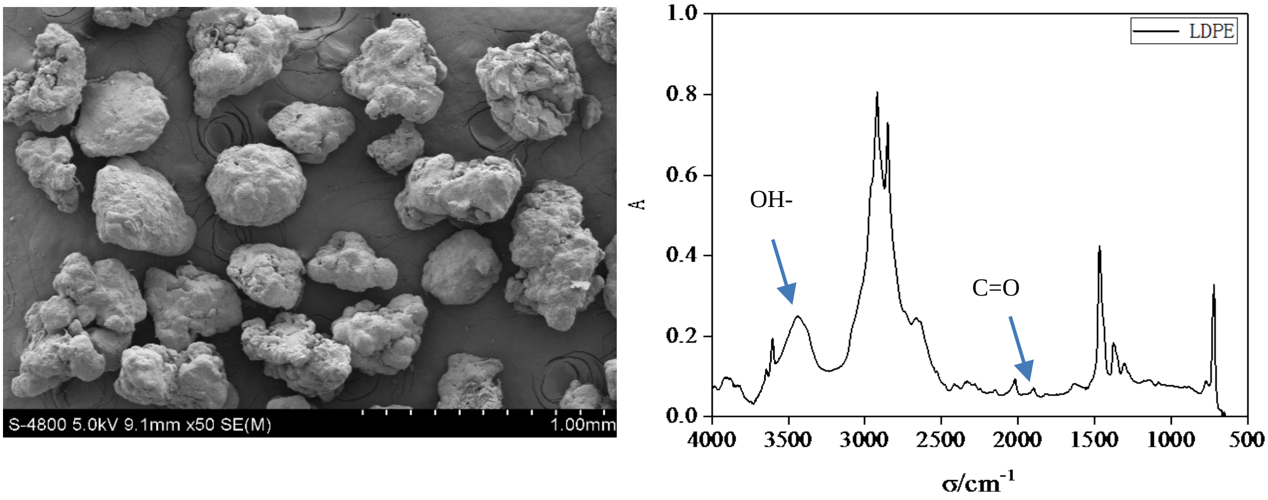
### 2.2.3. LDPE Microplastic Adsorption Experiment

The adsorption of Cd on LDPE microplastics adopts the standard adsorption thermodynamic experimental method (Gu et al., 2021). In each set of adsorption experiments, the concentration of LDPE microplastics was 2000 mg·L$^{-1}$, and the set concentrations of Cd were 0.15 mg·L$^{-1}$, 0.40 mg·L$^{-1}$, 0.80 mg·L$^{-1}$, 1.60 mg·L$^{-1}$, 2.50 mg·L$^{-1}$. After 12 h of rotational shaking and 24 h of standing the filtrate was filtered through 0.22 μm filter membrane and the Cd concentration was determined by flame atomic absorption. The Cd concentration in the filtrate was determined by flame atomic absorption spectrophotometer. At the same time, the actual concentration of Cd in the blank control (without LDPE microplastic) was determined. The adsorption amount of Cd was obtained by calculating the difference of Cd concentration between blank sample and supernatant.

## 3. Results and Discussion

### 3.1. LDPE Characterization

It can be seen from **Figure 2** that LDPE micro plastic has rough surface and uniform particle size. The infrared spectrum shows the spectral characteristics of polyethylene. There are weak carbonyl groups near 1700 cm$^{-1}$ and weak hydroxyl groups near 3400 cm$^{-1}$. Therefore, LDPE used in the experiment may have slight oxidation.



(a) (b)

**Figure 2.** SEM image (a) and FTIR spectra (b) of pristine LDPE microplastics.

## 3.2. Combined Effect of LDPE Cd on *Solanum nigrum* L.

### 3.2.1. Effect of LDPE Cd on *Solanum nigrum* L. Root

The plant height, root length and root fresh weight of *Solanum nigrum* L. under the joint influence of microplastics and cadmium are shown in **Figure 3**. LDPE alone can promote the plant height of *Solanum nigrum* L., which was enhanced with increasing LDPE concentration. LDPE-$Cd^{2+}$ inhibited the plant height of *Solanum nigrum* L. in varying degrees. Only adding Cd had the greatest impact on the plant height of *Solanum nigrum* L., so LDPE promoted the growth of plant height of *Solanum nigrum* L. to a certain extent.

Under the influence of LDPE alone, the taproot of *Solanum nigrum* L. was short and insignificant, with many fibrous roots. With the increase of LDPE concentration, the taproot length of *Solanum nigrum* L. decreased. The taproot of *Solanum nigrum* L. was significantly affected by cadmium alone and LDPE-$Cd^{2+}$. Cadmium alone affected the growth of taproot length of *Solanum nigrum* L., and the taproot length of *Solanum nigrum* L. under the joint influence of LDPE-$Cd^{2+}$ was greater than that under the condition of no pollution and single LDPE; With the increase of LDPE concentration, the length of taproot was slightly inhibited.

LDPE alone had no significant effect on the fresh weight of *Solanum nigrum* L. root within 10 days, but it could increase the fresh weight of *Solanum nigrum* L. root after 17 days. Cadmium alone promoted the fresh weight of *Solanum nigrum* L. root for 10 days, but had no significant effect on the fresh weight of *Solanum nigrum* L. root for 17 days. LDPE-$Cd^{2+}$ compound pollution inhibited the fresh weight of *Solanum nigrum* L. root for 10 days, and had no significant effect on the fresh weight of *Solanum nigrum* L. root for 17 days.

Heavy metals significantly inhibited the fresh weight of *Solanum nigrum* L. root. The migration and accumulation of metals from roots to leaves during plant growth inhibited the size of *Solanum nigrum* L. leaf area. However, heavy

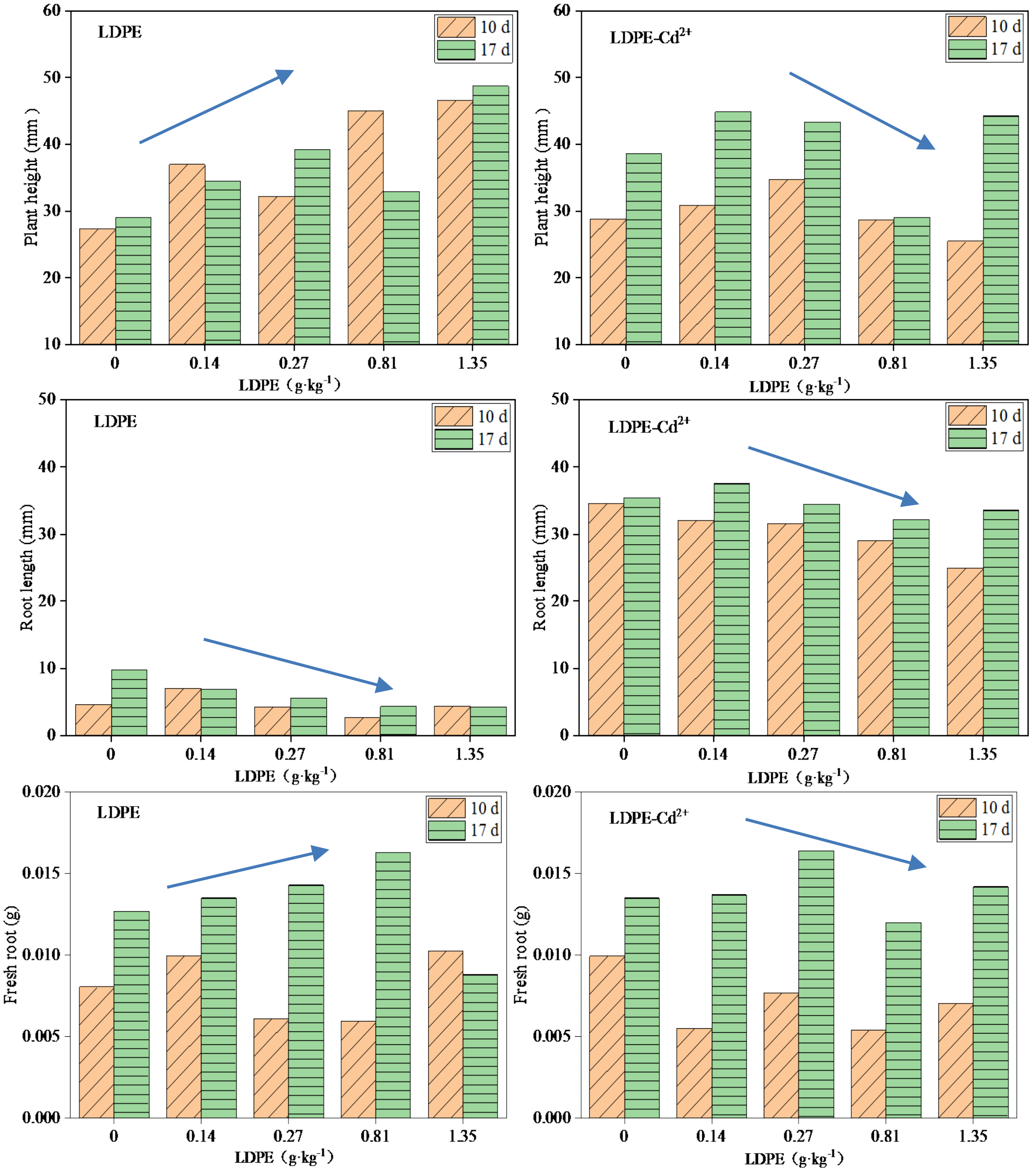


Figure 3. Effects of LDPE on roots of *Solanum nigrum* L. seedlings.

metal Cd had no significant inhibitory effect on the aboveground part of *Solanum nigrum* L. seedlings, so the change of plant height was weakly. With the addition of microplastics, the biological effectiveness of Cd in *Solanum nigrum* L. plants was affected. Microplastics adsorb or accumulate in the roots of *Solanum nigrum* L. and form a physical barrier, thus affecting the growth of the main roots of the plant. Bosker et al. found that nano- and microplastics can accumulate in the stomata of Cress (*Lepidium sativum*) seed coats in the germination process and form a physical barrier, thus delaying the seed germination and root growth process (Bosker et al., 2019). Souza Machado et al., 2019 also found that six different microplastics (properties and species) were also observed to significantly alter biomass, root traits and soil microbial activity in onion (*Allium fistulosum*). Boots et al., (2019) also found that three microplastics (biodegradable polylactic acid, high density polyethylene and Synthetic Fiber) reduced growth target (biomass, germination and chlorophyll content) of perennial ryegrass (*Lolium perenne*), Dong et al., (2019) found that microplastic particles increased the toxicity of arsenic to rice seedlings, and that polystyrene and polytetrafluoroethylene microplastics inhibited root activity and diphosphoribulose carboxylase activity in concert with the heavy metal arsenic to reduce rice biomass. Therefore, the ecotoxicity of microplastics to plants may depend on both plant and microplastic types.

### 3.2.2. Effects on *Solanum nigru*m L. Leaves

LDPE alone inhibited the leaf area of *Solanum nigrum* L., and the leaf area decreased with the increase of LDPE concentration. LDPE-$Cd^{2+}$ compound pollution inhibited the leaf area of *Solanum nigrum* L. within 10 days and promoted the leaf area after 17 days. Chlorophyll is the main participant in plant photosynthesis. They are continuously synthesized and decomposed in plant growth and metabolism. Under adverse conditions, the change of chlorophyll value can be understood as a kind of self-protection of plants against adverse environment (Zhang et al., 2018). LDPE makes the chlorophyll of *Solanum nigrum* L. generally show a downward trend. According to **Figure 4**, the chlorophyll content decreases with the increase of LDPE concentration. When the concentration was 0.81 $mg \cdot kg^{-1}$, the chlorophyll decreased to the lowest value, and then increased with the increase of LDPE concentration. The effect of LDPE-$Cd^{2+}$ compound pollution on photosynthesis was not obvious at 10 days, which was consistent with the results of 10 days exposure test of Azolla in Mateos-Cardenas et al., (2019). Our study found that the chlorophyll content of *Solanum nigrum* L. decreased significantly on the 17th day. Whether it was single LDPE or LDPE-$Cd^{2+}$ composite pollution, the chlorophyll content of *Solanum nigrum* L. showed a trend of “medium concentration inhibition and high concentration promotion”. The reason may be that the adsorption and absorption of *Solanum nigrum* L. to microplastics mainly depended on the properties of microplastic particles. At medium and high concentrations, the microplastics are continuously agglomerated, and the particle size of the agglomerated microplastics gradually increases. The pore blockage on the root surface caused by adhering to the plant root system reduces the contact between *Solanum nigrum* L. and the microplastics, thus reducing its photosynthetic stress. Low levels of soil microplastic residues, soybean could reduce the effects of stress through its own antioxidant system as the reproductive period increased; at higher levels, various physiological and

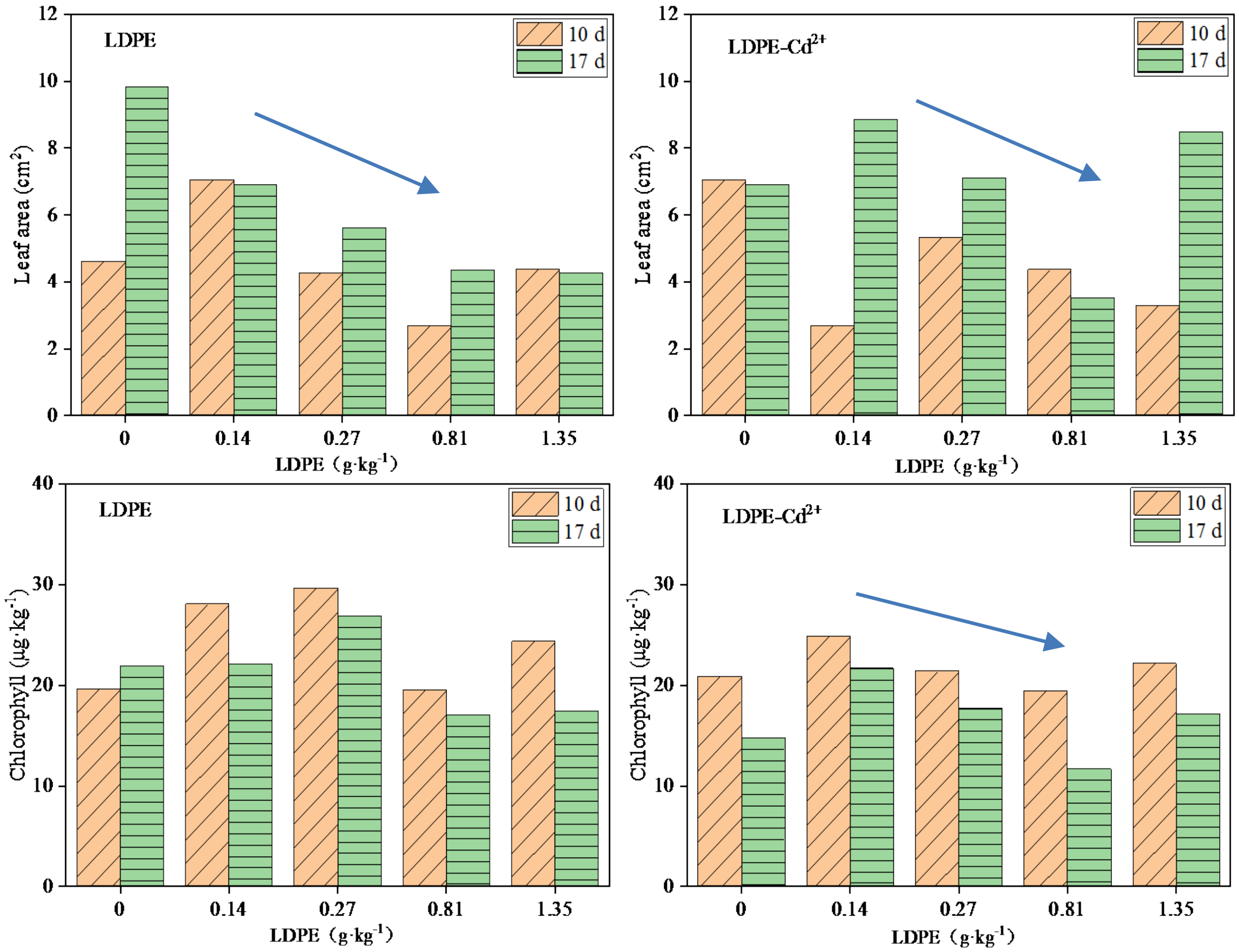


**Figure 4.** Effect of LDPE on blade of *Solanum nigrum* L.

biochemical indicators such as leaf area, plant height, and root vigor were affected to a greater extent. It has been found that microplastics affect plant water uptake as one of the possible toxicity mechanisms, and the phytotoxicity of polyethylene microplastics is closely related to particle size and concentration, the smaller the particle size is ,the higher the concentration is, the stronger phytotoxic it may be to plants.

### 3.2.3. Role of LDPE and Cd

In order to reveal the combined toxicity mechanism of LDPE microplastics and Cd on *Solanum nigrum* L., the adsorption thermodynamics of LDPE microplastics for $Cd^{2+}$ was determined. As shown in Figure 5, LDPE microplastics can adsorb $Cd^{2+}$. The Freundlich adsorption coefficient $K_F$ of LDPE microplastics for $Cd^{2+}$ is 73.1 ± 6.9 $mg^{1-n}L^{n}\cdot kg^{-1}$, and n is 0.65 ± 0.05, and the $K_D$ value is 85.12 $ml\cdot g^{-1}$. The adsorption of $Cd^{2+}$ on LDPE microplastics is realized by the electrostatic attraction between the negative charge carried on the surface of LDPE microplastics and $Cd^{2+}$. Similar research results have been reported in the literature. The oxygen-containing functional groups on the surface of naturally agedmicro

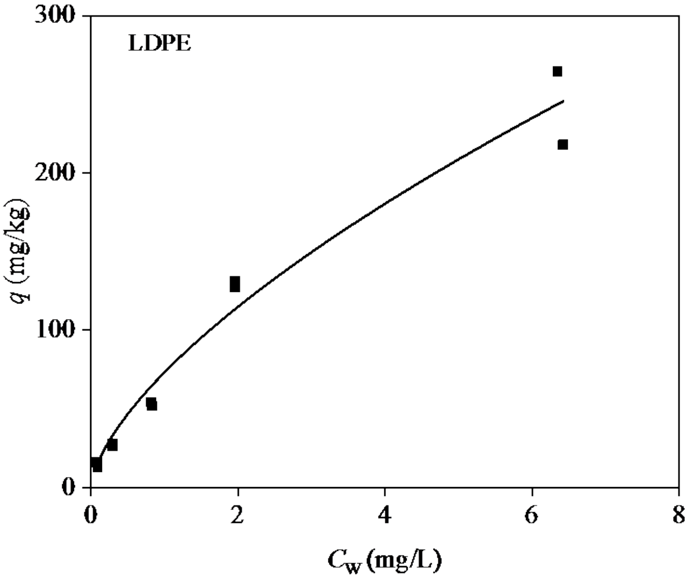


**Figure 5.** The adsorption isotherm of Cd on LDPE microplastics.

plastics can improve the adsorption capacity of heavy metal lead (Gravand et al., 2020). Therefore, the adsorption of Cd by LDPE microplastics may lead to the uptake of such particles by the roots of *Solanum nigrum* L., so as to improve the bioavailability of Cd and inhibit the growth and development of *Solanum nigrum* L.

The results of (Zong et al., 2021) showed that PS microplastics (0.5 μm, 100 mg·L$^{-1}$) without significant effect on the growth and Photosynthesis of wheat seedlings. The adsorption of copper and cadmium by PS microplastics is mainly chemisorption. PS microplastics can reduce the accumulation of Cu and Cd in wheat seedlings and mitigate the toxic effect of heavy metals on wheat seedlings. Compared with the single heavy metal treatment, PS microplastics and heavy metal composite treatment increased chlorophyll content and enhanced photosynthesis. These findings indicate that PS microplastics (0.5 μm, 100 mg·L$^{-1}$) can alleviate the bioavailability and toxicity of copper and cadmium.

## 3.3. Impact of LDPE on Soil

### 3.3.1. Effect of LDPE on Soil Physical and Chemical Properties

It can be seen from **Figure 6** that the initial pH of the cold black soil used in this experiment is 6.42. After after planting *Solanum nigrum* L., the soil pH decreases continuously with the increase of LDPE concentration. At 10 days, with the increase of single LDPE concentration, the pH of soil decreased by 0.9%, 1.7%, 2.6%, 2.6% and 3.3% respectively. And single Cd contamination decreased soil pH by 4.0%. With the increase of LDPE concentration, the LDPE-Cd$^{2+}$ compound pollution make the pH of soil decreased by 2.3%, 4.0%, 5.1% and 4.7%. The effect of cadmium on soil pH is stronger than that of micro plastics. Low concentration LDPE (0.27 mg·kg$^{-1}$) can alleviate the stress of cadmium pollution on plant roots. The combined pollution of high concentration LDPE (0.81 mg·kg$^{-1}$,

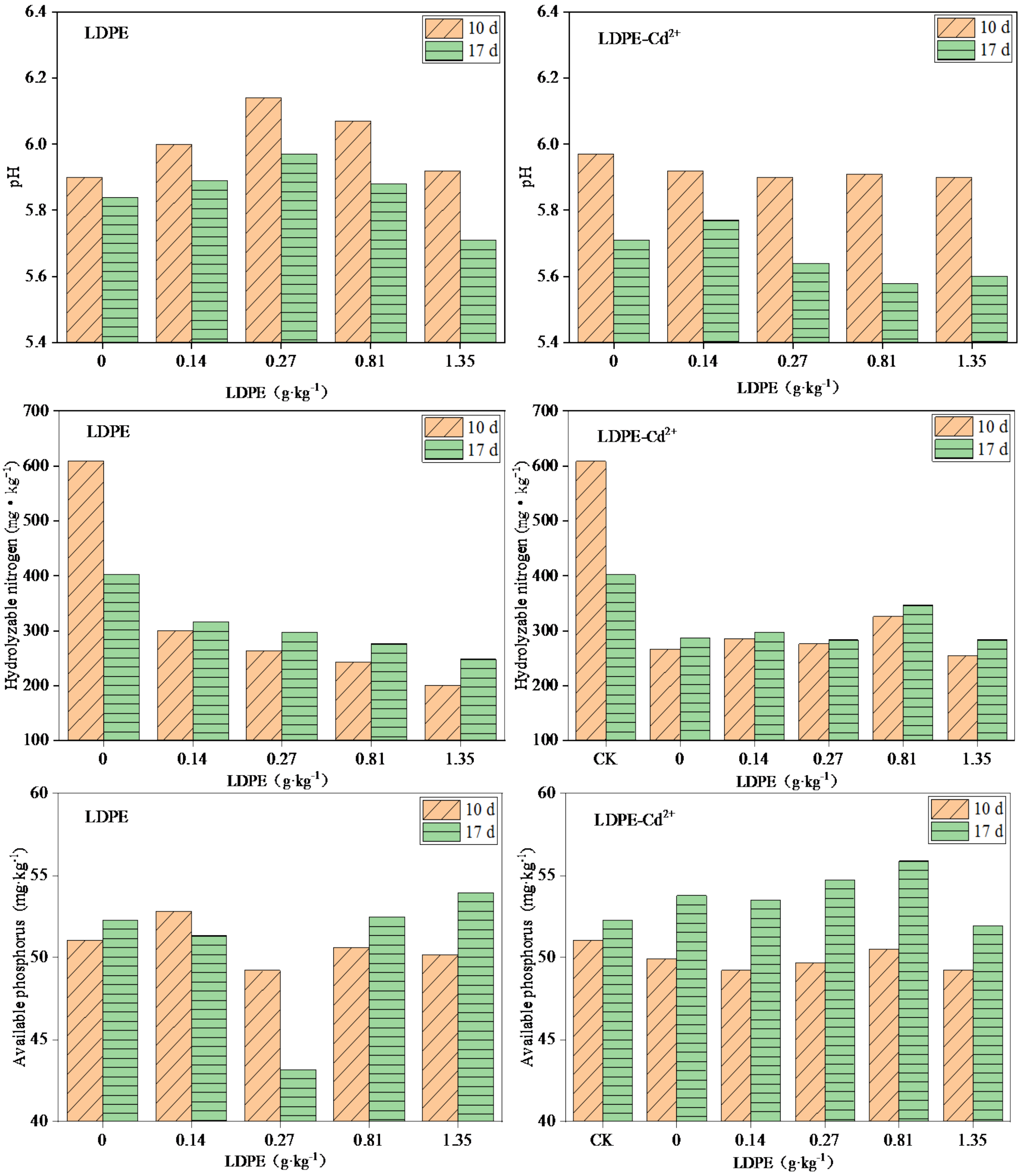


**Figure 6.** Effects of LDPE and cadmium on soil physical and chemical properties.

1.35 mg·kg$^{-1}$) will reduce soil pH, which may be caused by the release of organic acids and enzymes from root exudates stimulated by microplastics, so as to create a better growth environment for plants to absorb nutrients. Under the single LDPE pollution and LDPE-Cd$^{2+}$ combined pollution, medium and high concentrations (LDPE 0.27 mg·kg$^{-1}$, 0.81 mg·kg$^{-1}$) have the greatest impact on soil pH, showing a trend that low concentration promotes, medium and high concentration inhibition. Under the influence of LDPE, as time went by, the pH of the soil decreased. Compared with single LDPE pollution, LDPE-Cd$^{2+}$ compound pollution significantly reduced the pH of soil, and with the increase of LDPE concentration, the pH of soil decreased.

Hydrolyzed nitrogen in soil is the nitrogen that can be absorbed and utilized by crops in the current season, which can better reflect the recent nitrogen supply of soil. It includes inorganic nitrogen and some easily decomposed organic nitrogen, which can be directly absorbed by plant roots and plays a very important role in soil fertility (Yan et al., 2014). High concentration of cadmium pollution will increase the hydrolyzed nitrogen in soil. This study found that both LDPEs alone and LDPE-Cd$^{2+}$ composite pollution will increase the hydrolyzed nitrogen in soil. The stress degree of cadmium pollution alone on plants is higher than that of LDPE pollution alone. Low concentration compound pollution will promote the absorption of hydrolyzed nitrogen, which shows that LDPE can alleviate the impact of cadmium stress on the absorption of hydrolyzed nitrogen by roots of plants.

It can be seen from **Figure 6** that after 10 days, compared with the blank control, the content of hydrolyzed nitrogen in LDPE alone and LDPE-Cd$^{2+}$ composite pollution showed an upward trend. Under the influence of LDPE alone, with the increase of LDPE concentration, the soil hydrolyzed nitrogen decreased by 2.7%, 5.5%, 5.4% and 7.8%, and the hydrolyzed nitrogen decreased by 3.3% due to cadmium alone, and the hydrolyzed nitrogen decreased by 1.9%, 1.1% 3.3% and 4.7% due to LDPE-Cd$^{2+}$ composite pollution. In comparison, it was found that the low concentration of LDPE reduced the amount of free cadmium in the soil by affecting soil pH, changing the existing form and migration mode of Cd$^{2+}$ in the soil and causing its complexation, thus reducing the uptake of heavy metal Cd by the roots of *Solanum nigrum* L., and thus promoting the uptake of hydrolyzed nitrogen by the roots.

Under the influence of LDPE, the soil hydrolytic nitrogen decreased with the increase of time, and the soil hydrolytic nitrogen decreased with the increase of LDPE concentration. The composite pollution of LDPE-Cd$^{2+}$ reduced the hydrolyzed nitrogen of soil, but did not change with the change of LDPE concentration. The effect of Cd on soil hydrolytic nitrogen was higher than that of LDPE.

Available phosphorus refers to the phosphorus that can be absorbed and utilized by plants in soil. It is not only a key index indicating the availability of phosphorus in soil, but also one of the important indexes to evaluate soil fertility and determine crop yield. Plants usually produce a small amount of organic acid anions to dissolve Phosphorus in soil (Zhang et al., 2021) to deal with phosphorus deficiency. Organic acids, including humic acid and fulvic acid, can inhibit the precipitation of phosphate minerals, improve the bioavailability of phosphorus and increase the availability of micronutrients. **Figure 6** shows that the effect of LDPE alone on soil available phosphorus is irregular. LDPE-Cd$^{2+}$ compound

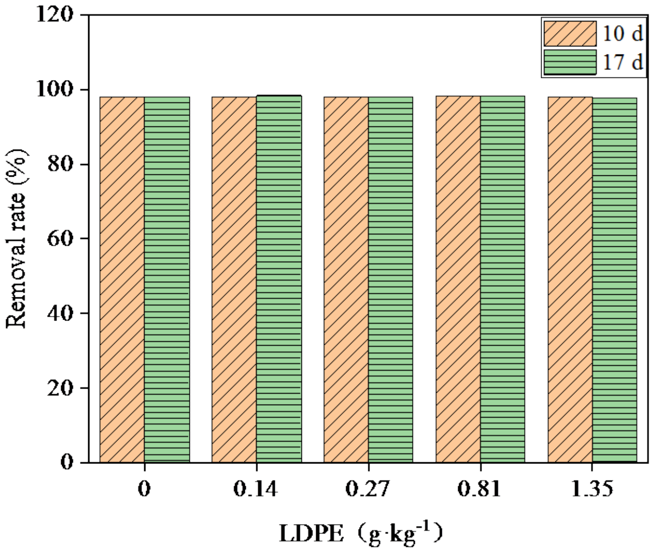


**Figure 7.** Effect of LDPE on cadmium removal from soil by *Solanum nigrum* L.

pollution increased soil available phosphorus. As time went by, soil available phosphorus decreased slightly at 10 days, while soil available phosphorus increased at 17 days. With the increase of LDPE concentration, soil available phosphorus increased by 8.7%, 10.2%, 10.6% and 5.5%, indicating that cadmium stress has a greater impact on soil available phosphorus than LDPE, and low concentration LDPE will alleviate the stress of cadmium and promote the absorption of available phosphorus by plants. It is known that the changes in pH show a rise followed by a fall, thus also causing an increase in soil phosphorus content.

### 3.3.2. Effect of LDPE on Cd Removal Rate in Soil

It can be seen from **Figure 7** that the removal rate of heavy metals in soil by *Solanum nigrum* L. is more than 97%, which does not change with the concentration of LDPE. Therefore, LDPE has no significant effect on the removal efficiency of cadmium by *Solanum nigrum* L. under the concentration of $Cd^{2+}$ in this study (20 mg·kg$^{-1}$).

The research results of (Zong et al., 2021) show PS microplastics (0.5 μm, 100 mg·L$^{-1}$) can alleviate the bioavailability and toxicity of copper and cadmium. Microplastics increased the effectiveness of Cd in soil but also reduced plant root biomass, which could be one of the reasons to explain that there was no significant change in plant cadmium concentration and accumulation (Wang et al., 2020; 2021). In addition, microplastics can change soil properties and soil biophysical environment, such as soil structure, hydrodynamics and aggregation (de Souza Machado et al., 2019), thus affecting the bioaccumulation and bioavailability of cadmium in soil.

## 4. Conclusion and Outlook

Heavy metals significantly inhibited the fresh weight of *Solanum nigrum* L. root.

Microplastics interfered with the inhibitory effect of Cd on the taproot length and plant height of *Solanum nigrum* L. LDPE-$Cd^{2+}$ compound pollution inhibited the fresh weight of roots in the early growth stage of *Solanum nigrum* L. seedlings. Heavy metal Cd and LDPE alone inhibited the aboveground part of *Solanum nigrum* L. seedlings. LDPE-$Cd^{2+}$ compound pollution inhibited the leaf area of the early growth stage of *Solanum nigrum* L. seedlings and promoted the leaf area of the later growth stage of *Solanum nigrum* L. seedlings. The chlorophyll content of *Solanum nigrum* L. seedlings in the later growth stage showed a trend of "medium concentration inhibition and high concentration recovery" due to single LDPE and LDPE-$Cd^{2+}$ combined pollution. The electrostatic interaction between LDPE microplastics and Cd has the potential to co-interact with lobelia roots, thereby increasing the bioavailability of Cd and inhibiting the growth and development of *Solanum nigrum* L.

LDPE-$Cd^{2+}$ compound pollution significantly reduced the soil pH than LDPE alone, and the soil pH decreased with the increase of LDPE concentration. LDPE alleviated the effect of Cd stress on plant roots uptake of hydrolytic nitrogen and promoted root uptake of hydrolytic nitrogen. The effect of Cd on soil hydrolyzed nitrogen is higher than LDPE. Cadmium stress has a greater impact on soil available phosphorus than LDPE, and low concentration of LDPE will alleviate the stress of cadmium and promote the absorption of available phosphorus by plants. LDPE had no significant effect on the removal efficiency of cadmium by *Solanum nigrum* L.

The presence of large amounts of microplastics in terrestrial ecosystems, especially in soils, has significant effects on the germination and physiological growth and developmental characteristics of higher plants. Higher plants are closely related to human life, and the toxicity and potential risk of microplastics to higher plants cannot be ignored. There are many types of microplastics, complex composition and wide variation in property, and their effects on plants and related microor-ganisms, inter-rhizosphere flora structure, etc. are regulated by many environ-mental factors. In the future, we should explore more about the effects of micro-plastics on the physiological growth characteristics of different types of plants and find the mechanism of microplastic pollution on plants.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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