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The addition of degradable activators enhances Sedum alfredii phytoremediation efficiency in Cd-contaminated soils

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Abstract

Soil cadmium (Cd) pollution is a critical environmental issue that requires urgent remediation. Sedum alfredii, known for its high biomass, strong stress tolerance, and suitability for harvesting, serves as an excellent hyperaccumulator. This study used field experiments to investigate the enhancement of Cd phytoremediation in soil using three activators: citric acid (CA), malic acid (MA), and polyaspartic acid (PASP). The results showed that the biomass of Sedum alfredii was increased by 8.95%-28.37% by the addition of these activators, significantly boosting its Cd accumulation efficiency, with an average removal rate increase of 12%. Among all activators, CA exhibited the most substantial enhancement effect, with enrichment coefficients of 36.26% and 11.56% for the aboveground parts and roots of Sedum alfredii, respectively, and a 21.15% increase in Cd removal rate. Although PASP had less pronounced effect on biomass and Cd uptake, with decreases of 15.25% and 35.34% in the aboveground parts and roots, respectively, it significantly impacted soil Cd speciation and increased the activation rate by 20%.

Highlights

1. Cd remediation efficiency of Sedum alfredii up to 25.97% with CA treatment

2.The application of CA markedly increased both the biomass of Sedum alfredii and its cadmium uptake.

3.The activation rate increased by 20% under polyaspartic acid treatment.

Introduction

Cadmium(Cd) in soil may be accumulated in crops and plants through surface runoff, irrigation, sediment deposition, etc., and transmitted through food chain, posing threats to human health(Wang et al. 2021). Seeking economically effective methods for the remediation of cadmium-contaminated soil is urgent. Among the Cd-contaminated soil remediation technologies, phytoremediation is the most promising method for heavy metal pollution due to its low cost and environmental friendliness(Chi et al. 2024).

Phytoremediation is employed using hyperaccumulator plants to absorb heavy metals from the soil. Heavy metals are taken up from the soil, water, or solid sediments into the plant with the assistance of their root systems and associated microorganisms. Then they are transported to the above-ground parts before being harvest and achieve the goal of heavy-metals removal (Mahar et al. 2016). Among these plants, the annual or perennial succulent herb Sedum alfredii stands out as an excellent Cd hyperaccumulator due to its high biomass, strong stress tolerance, and suitability for harvesting(Du et al. 2022). However, phytoremediation technology has the disadvantages of a long remediation and treatment cycle and low efficiency(Jing et al. 2015). To address these limitations, phytoremediation enhancement techniques have been developed, including chemical enhancement, microbial enhancement measures, agronomic measures, and genetic modification engineering. The bioavailability

of soil contaminants is improved or plant growth is effectively promoted through chemical enhancement methods, significantly improving the performance of plants in soil remediation. It is made one of the effective measures to overcome the inefficiency and time-consuming nature of phytoremediation. Chemical enhancement remediation technology, through the addition of activators, is used to alter the form and bioavailability of heavy metals in the soil, thereby increasing the ability of plants to extract heavy metals from the soil.

Activators can be classified into three main types:1.Synthetic Aminopolycarboxylic Acids: These include ethylenediaminetetraacetic acid (EDTA) and glutamic acid diacetic acid (GLDA);2.Natural Aminopolycarboxylic Acids: These include ethylenediaminedisuccinic acid (EDDS) and nitrilotriacetic acid (NTA);3.Natural Small-Molecule Organic Acids: These include citric acid (CA), malic acid (MA), and tartaric acid (TA)(Lee &Sung 2014).Among these, synthetic aminopolycarboxylic acids like EDTA and GLDA can enhance the dissolution of heavy metals in the soil, forming metal complexes that increase mobility and improve metal transfer to the roots and above-ground parts of plants. However, the permeability of plant root cell membranes can be disrupted by these synthetic activators, plant growth can be inhibited, and they are difficult to degrade in the soil, causing toxicity to plants, soil animals, and microorganisms, leading to secondary pollution(Zaier et al. 2010). For example, under EDTA treatment, plant growth is limited, manifesting as low seed germination rates, wilting, chlorosis and necrosis of leaves, and reduced transpiration(Barrutia et al. 2010, Guo et al. 2018, Jez &Lestan 2016).

Low molecular weight natural organic acid activators, such as citric acid (CA) and malic acid (MA), are harmless to plants in practical applications and are easily degradable(Zhi-guo et al.). Moreover, soil microbial activity can be enhanced and plant growth can be promoted by them. The mechanisms to increase plant heavy-metals uptake include: (1)Lowering Soil pH, heavy metals that are in an insoluble state or fixed in soil minerals are released(Turgut et al. 2004);2. Hydrogen ions dissociated from acidic groups are adsorbed onto the cation adsorption sites on the surfaces of soil particles and minerals, resulting in the displacement of metal ions (Alozie et al. 2018);3. Some heavy metals can be formed into soil-chelating agent-heavy metal complexes with low molecular weight organic acids and be immobilized in the soil, reducing the migration of heavy metals(Lin et al. 2021). Polyaspartic acid (PASP), a biodegradable surfactant with multiple carboxyl and hydroxyl groups(Wang et al. 2021), is synthesized from L-aspartic acid(Wu et al. 2021). It can be effectively used to form complexes with Cd^{2+}, replacing Cd in the soil, thereby reducing the toxicity of Cd to plants(Yifeng &Yuyang 2008) and improving the extraction efficiency of heavy metals by rapeseed and black nightshade(Liu et al. 2023). Additionally, the activity of antioxidant enzymes in plants can be increased by PASP, thereby enhancing their defense against heavy metal stress(Li et al. 2023).

The enhancement of phytoremediation for heavy metal-contaminated soil using EDTA(Nawaz et al. 2023), PASP (Zhang et al. 2019), CA(Afshan et al. 2015), and MA(Stojanov et al. 2024) has been validated in pot experiments. However, pot experiments are conducted under controlled conditions, and it is impossible to fully simulate field application conditions such as climatic changes, soil background conditions like moisture, nutrients, and microbial environment, and the rhizosphere environment resulting

from the interaction between plant roots and field soil(R &Z 2023). This study selected three natural organic acid activators: citric acid (CA), malic acid (MA), and polyaspartic acid (PASP), and investigated the enhancement effects of these activators, both individually and in combination, on the remediation of soil Cd contamination by Sedum plumbizincicola through field experiments.

Materials and Methods

Plant material, soil properties and field profile

The test plants were obtained from Southeast Sedum Breeding Base, Qingyuan, China. The location of the experimental field is shown in Fig. 1, which is located in Sanshui District, Foshan City (latitude 23°06'N, longitude 112°84'E), which belongs to the subtropical monsoon humid climate zone. Agricultural soils in the area are contaminated by Cd from sewage irrigation, with an average pH of 7.23, an organic matter (SOM) content of about 21.04 g/kg, and a cation exchange capacity (CEC) of 26.6 cmol/kg. Two rounds of Sedum plumbizincicola remediation experiments were conducted from November 2018 to July 18, 2020. The first round was conducted from November 11, 2018, to April 2, 2019, without the addition of activators. The planting of Sedum plumbizincicola reduced the Cd concentration in the soil from 0.98 mg/kg to 0.89 mg/kg, with a removal rate of 9.18%. From February 28, 2020, to July 18, 2020, this study further conducted a natural activator-enhanced remediation of Cd-contaminated soil using Sedum plumbizincicola.

Field experiment

The experimental field was divided into 6 columns and 3 rows, with each plot measuring 8 meters in length and 11 meters in width. There are 18 plots in total with a 20 cm gap between plots.. After ridge division, plowing, and mulching, 42 kg/acre of potassium humate was added and evenly plowed into the soil. The transplanting distance of Sedum plumbizincicola was approximately 20 cm. One month after transplanting, activators were added. Six treatments were set up, including control check (CK), CA (42 kg/acre), MA (42 kg/acre), PASP (42 kg/acre), CA (21 kg/acre) + PASP (21 kg/acre), and MA (21 kg/acre) + PASP (21 kg/acre), with each treatment replicated three times.

Sample collection, preparation and analysis

Five spots of Southeastern Sedum were collected from each test plot as a mixed sample, for a total of 18 soil samples and 18 plant samples.

The soil pH was measured using the electrode method. A soil-to-water ratio of 2.5:1 was oscillated for 5 minutes, allowed to stand for 30 minutes, and the supernatant was measured with a pH meter. The absorbance of Cd in the test solution was measured using a graphite furnace atomic absorption spectrometer, and the Cd content was calculated. The Tessier five-step extraction method was used to measure the speciation of Cd in the soil(Li-wei &Hai-ying 2020).

Sedum alfredii was thoroughly washed with tap water to remove impurities adhering to the entire plant, followed by at least three rinses with deionized water. The plants were then drained, and surface moisture was removed with filter paper. The plants were separated into aboveground and underground parts, and their fresh weight was recorded before being dried in an oven at 75°C. The dried samples were then ground, sieved, and prepared for analysis.

Statistical analysis of data

Mean and standard deviation of experimental data. One-way analysis of variance (ANOVA) was performed using spss.

The removal rate of soil cadmium (Cd) was calculated using the following formula:

$$EXEF_{HM} = \frac{C_0 - C_{Cd}}{C_0} * 100\% \quad (1)$$

Where, $EXEF_{HM}$ represents the removal efficiency of soil cadmium,%;C_0 is the initial cadmium content in the soil;C_{Cd} is the cadmium content in the soil after remedi- ation,mg/kg;

The ratio of Cd taken up by plants to Cd in the exchangeable and carbonate-bou- nd morphological in the soil as an activated part of total Cd is called the activation rate.

The activation rate of Cd is calculated as follows:

$$\eta = \frac{C_0 - C_{Cd} + C_e}{C_0} * 100\%$$

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η represents the activation rate of soil cadmium,%;C_e represents the sum of the concentrations of exchangeable and carbonate-bound Cd in the soil after remediation, mg/kg;

The bioconcentration and transport of Cd by Southeast Sedum were estimated by transport factor (TF) and bioconcentration factor (BCF).

The bioconcentration factor (BCF) is an index of the ability of plants to absorb Cd from the soil into their above-ground and root systems. It is calculated as follows:

$$BCF = \frac{C_a}{C_s} \quad (3)$$

Where Ca (mg/kg) indicates the Cd concentration in the dry branches at harvest and Cs is the initial soil Cd concentration.

The translocation factor (TF) gives an indication of the plant's ability to translocate metals from roots to above-ground parts. This parameter was calculated as follows:

$$TF = \frac{C_a}{C_r} \quad (4)$$

where Ca (mg/kg) and Cr (mg/kg) represent the Cd concentrations in the plant aboveground and in the roots, respectively.

Results and Discussion

Cadmium Removal

The removal of cadmium from soil through phytoremediation is influenced by factors such as the geographical location of the experiment, soil physicochemical properties, plant type, and pollution load. The removal rates of soil Cd are shown in Fig. 2. The removal rate of Cd by the CK group was 4.82%. After activators were added, the soil Cd removal rates ranged between 9.27% and 25.97%, showing considerable variation,with an average removal rate increase of 12%.The highest Cd removal rate was achieved with the addition of CA, reaching 25.97%, which was 21.15% higher than that of the CK group. The second highest removal rate was achieved with MA, which increased by 16.54%. The enhancement effect of the activators PASP + MA and PASP + CA on the remediation of Cd by Sedum plumbizincicola was not significant.

In this study, the enhanced Cd removal rate by Sedum alfredii using CA shows some differences compared to related reports of CA-enhanced phytoremediation in the literature (Table 1). There may be three main reasons for this:1. Plant Species Influence. Compared to Celosia argentea Linn(Chao et al. 2023), Sedum alfredii is identified as a hyperaccumulator plant with a strong potential to absorb and accumulate heavy metals;2. Pollution Load. The accumulation of Cd by plants generally decreases with an increase in soil heavy metal concentration(Nevel et al. 2007). Plant growth and biomass can be affected by excessive Cd through reduced mineral nutrient uptake and disrupted biochemical metabolic processes(Gill et al. 2011). Once heavy metals enter the plant, cell division, photosynthesis, respiration, and mineral nutrient absorption can be adversely affected, leading to symptoms such as curled young leaves, stunted growth, and significantly reduced biomass(Song et al. 2014).For example, when the initial concentration was 20.09 mg/kg, the remediation effect of Sedum alfredii on Cd was not significant(Liu et al. 2008); 3.Experimental Conditions:Compared to field experiments, smaller volumes and fewer cultivated plants are involved in pot experiments, making the control of soil, fertilizer, and water conditions easier.This facilitates the regulation of soil temperature and moisture content, promoting Cd absorption by Sedum alfredii.The Cd content in the aboveground and root parts can reach several hundred mg/kg(Liu et al. 2008), leading to significant differences in Cd accumulation by individual Sedum alfredii plants between pot and field experiments(Sun et al. 2009). Compared to CA and MA, weaker bonds with Cd are formed by PASP. When mixed with MA or CA, the rhizosphere environment of Sedum alfredii can be affected by PASP, resulting in an insignificant enhancement effect of the PASP + CA and PASP + MA combinations on the remediation by Sedum alfredii.

Activation of Cd in Soil

The forms of heavy metals in soil are important factors affecting their mobility and bioavailability. Heavy metals in soil are classified into five forms by the Tessier five-step extraction method: exchangeable, carbonate-bound, Fe-Mn oxide-bound, organically bound, and residual forms. Most plants can only absorb heavy metals that are in dissolved form in the soil solution, weakly bound to soil particles (exchangeable form), and partially in the carbonate form, while those bound to the soil solid phase are difficult for plants to absorb(zhu, et al. 2008). In this study, the sum of the exchangeable, carbonate-bound, and the Cd extracted by Sedum alfredii in the remediated soil is considered the available form of soil Cd. The Fe-Mn oxide-bound and organically bound forms, which can transform into available forms under certain environmental conditions(Na et al. 2021), are defined as potentially available forms. Chemical activators promote the transformation of potentially available forms into available forms through processes such as acidification, complexation, precipitation, and redox reactions, thereby facilitating the phytoremediation of contaminated soil(Yang et al. 2021).

After enhanced remediation, the distribution of Cd forms in the soil is shown in Fig. 3. In the soil, Cd is mainly found in available and residual forms. Compared to the control group, the exchangeable and carbonate-bound forms of Cd were increased to varying degrees after treatment with activators. Under dynamic equilibrium, other forms of heavy metals gradually decreased. As shown in Fig. 2, the activation rate of Cd in the soil was increased by 19% and 20% under CA and PASP treatments, respectively. The carboxyl groups of PASP can be coordinated with Cd to form metal chelates(Fu et al. 2017), thereby rapidly and significantly increasing the availability of metals in contaminated soil. Small molecule organic acids like CA can introduce H^+ into the soil, altering the bioavailability of heavy metals, and can also form soluble chelates with heavy metal ions in the soil, promoting the adsorption of metal ions to soil particles and enhancing their activity and mobility(Kan-qi et al. 2023). Compared to CA, MA has a lower metal chelation ability(Hong-li, et al. 2008), but its activation effect on soil Cd was still notably observed.

Organic acids, in addition to promoting the transformation of Fe-Mn oxide-bound and organically bound forms into exchangeable forms, can also reduce Cd toxicity by enhancing the expression of enzymatic and non-enzymatic antioxidants and certain tolerance genes within plants. This helps maintain normal cell morphology(Zhang et al. 2020). As a result, the absorption of Cd ions and complexes by plants is enhanced, improving the phytoremediation capacity of plants for Cd-contaminated soil. This study found that both CA and MA not only increased the available Cd content in the soil but also promoted the growth of Sedum alfredii.

Absorption and remediation effect of Sedum alfredii on Cd

As shown in Fig. 4, the Cd content in the aboveground parts and roots of Sedum alfredii under different treatments were ranged from 6.61 to 10.63 mg/kg and 8.36 to 14.43 mg/kg, respectively. The Cd concentration in the aboveground parts was increased by 36.32% and 11.6% by the CA treatment, followed by the MA treatment, which respectively increased it by 7.69% and 11%.The hydroxyl or carboxyl

groups in CA and MA can form stable compounds with Cd, facilitating the absorption and accumulation of Cd by Sedum alfredii, further increased the Cd concentration in the stems and roots(Farid et al. 2018). However, under PASP treatment, the Cd content in the aboveground parts and roots of Sedum alfredii decreased by 15.25% and 35.34%, respectively, which was the lowest among all activator combinations. PASP did not significantly affect the Cd absorption capacity of Sedum alfredii, showing a marked difference from the results of pot experiments reported in the literature(Jiang et al. 2022). The reason might be that PASP, being an alkaline activator, increases soil pH and reduces H^+, which decreases the exchange of heavy metal cations adsorbed on the surface of soil particles with H^+, thereby slowing down the desorption of Cd from the surface of soil particles.

The key to increase accumulation of heavy metals in plants and enhanced phytoremediation with activators is to promote the dissolution of heavy metals in the soil and their translocation from plant roots to shoots. The Bioconcentration Factor (BCF) represents the ability of plants to accumulate heavy metals, while the Transport Factor (TF) indicates the translocation of heavy metals from the soil into the plant. The BCF and TF for each treatment group are shown in Table 2. Except for PASP, the Cd bioconcentration factor of Sedum alfredii was increased by all activator combinations. The BCF for Cd in the shoots and roots ranged from 7.43 to 11.95 and 9.4 to 16.21, respectively. The physicochemical conditions of the soil are altered by CA, being a weak acid, when applied, transforming the chemical forms of Cd from less absorbable to more absorbable by plants, thereby enhancing Cd uptake(Hui &Jing-jing 2021). CA increased the BCF of Cd in the shoots and roots of Sedum alfredii by 36.26% and 11.56%, reaching 11.95 and 16.21, respectively, the highest among all activator combinations.

The Transport Factor (TF) of plants is another crucial factor in phytoremediation (Li et al. 2020). Activators can increase the bioavailability of heavy metals and the permeability of root cell membranes, facilitating the entry of metal-chemical reagent complexes into the plant(Li et al. 2020). Compared to free metal ions, metal-chemical reagent complexes are more easily transported through the cortex to the xylem vessels because they do not bind to groups on the surface of root cortex cells, such as carboxyl groups or polysaccharides (Shahid et al. 2014). The TF values for each group showed no significant differences, ranging between 0.6 and 0.8, and were not significantly different from other field experiments(Chao et al. 2023). This indicated that the translocation of Cd from the roots to the shoots of Sedum alfredii was not significantly enhanced by the activators used in this study.

Table 2
Bioconcentration and translocation factors of Southeast Sedum after the activators addition

Treatment	BCF		TF
	Shoots	Roots	Shoots
CK	8.77 ± 2.8	14.53 ± 6.56	0.6 ± 0.04
CA	11.95 ± 3.57	16.21 ± 1.43	0.73 ± 0.14
MA	9.44 ± 2.27	16.21 ± 2.03	0.6 ± 0.18
PASP	7.43 ± 0.79	9.4 ± 1.14	0.8 ± 0.14
CA + PASP	9.2 ± 0.39	17.23 ± 3.76	0.6 ± 0.08
MA + PASP	9.14 ± 0.87	15.44 ± 4.91	0.66 ± 0.03
Values shown are the mean ± SD (n = 3)			

Biomass of Sedum alfredii

The biomass of plants is a key factor in determining the efficiency of phytoremediation(Xin-yu et al. 2023). Under the same conditions, plants with greater biomass can accumulate more heavy metals within their tissues(Xiaojuan et al. 2015). Biomass is influenced by a variety of complex factors, including soil heavy metal concentration, the type and concentration of chemical additives, climate change, and soil background conditions such as moisture, nutrients, and microbial environment. As shown in Fig. 5, activators increased the biomass of Sedum alfredii, with individual dry weights ranging from 17.02 g to 20 g, representing an increase of 8.95–28.37%. The addition of CA resulted in the greatest increases in both shoot and root dry weights, with increases of 28.35% and 30.3%, respectively.

The biomass of Sedum alfredii in this study was found to be higher than that reported in pot experiments (Table 1). A larger growth space is provided by field planting, allowing plant roots to be freely extended and water and nutrients to be absorbed. In contrast, root growth and, consequently, biomass accumulation are limited by container size in pot-grown plants. Additionally, more natural sunlight is received by field-grown plants, enhancing photosynthesis and promoting growth and biomass accumulation. Another reason is that a relatively low level of Cd contamination was present in the soil in the study area, resulting in less stress on the plants. When soil heavy metal concentrations are below the critical level that affects plant growth, no significant impact on plant development is observed. However, when soil heavy metal concentrations reach the critical threshold, plant growth can be severely inhibited(Hui &Jing-jing 2021). Excessive Cd can affect plant growth and biomass by reducing nutrient uptake and disrupting biochemical metabolic processes(Gill et al. 2011).

Most studies reported that the application of chemical reagents increased leaf necrosis and reduced plant biomass(Teng et al. 2022), while a few studies indicated that chemical reagent treatments did not

cause biomass loss and might even improve plant growth(He et al. 2019). In our study, plant shoot biomass, the amount of extracted Cd, and phytoextraction efficiency were significantly increased by the addition of CA relative to the control soil, suggesting that a beneficial effect on the growth of Sedum alfredii was provided by CA. This might be related to the structure of CA, which has three carboxyl groups, a special molecular structure, and charged properties that can participate in plant growth and development processes. Plant growth was promoted by CA by providing available phosphorus and iron compounds(Hawrylak-Nowak et al. 2015), decomposing humic substances, activating auxins, and mitigating stress damage to photosynthetic organs(Nardi et al. 2000, Zaheer et al. 2015). PASP was reported to enhance plant nutrient absorption and extend fertilizer utilization efficiency to improve plant nutrient levels(Yang et al. 2019). It was also believed to be capable of promoting seedling stem growth, root activity, chlorophyll content, and plant biomass(Hu et al. 2019). However, in this study, significant changes in the biomass of Sedum alfredii were not observed with the addition of PASP. This could be related to the active hydrothermal conditions in the study area, which promoted soil microbial activity and affected the effectiveness of PASP.

The biomass of phytoremediation plants is also related to the concentration of activators. If the concentration of activators is too high, it can adversely affect plant growth, leading to lower remediation efficiency(Xiaojuan et al. 2015). For example, EDTA has been shown to reduce the aboveground biomass of ramie(Jin et al. 2015) and inhibit the growth of ryegrass.

Correlation Analysis

A correlation analysis was conducted on soil pH, Sedum alfredii biomass, activation rate, Cd content in Sedum alfredii, and Cd removal rate. The correlation heatmap and linear relationship graph (Fig. 6) showed that the removal rate was significantly positively correlated with both the activation rate and biomass ($P < 0.05$), with correlation coefficients of 0.6 and 0.84, respectively. This indicated that the available Cd and the biomass of Sedum alfredii were important factors in improving the phytoremediation efficiency using activators. The bioavailability of soil heavy metals was determined to be a crucial factor in the amount of heavy metals absorbed by plants. Plants with larger biomass were found to accumulate more heavy metals in their roots and stems, thereby increasing the soil Cd removal rate. A correlation analysis was conducted on soil pH, Sedum alfredii biomass, activation rate, Cd content in Sedum alfredii, and Cd removal rate. The correlation heatmap and linear relationship graph (Fig. 6) showed that the removal rate was significantly positively correlated with both the activation rate and biomass ($P < 0.05$), with correlation coefficients of 0.6 and 0.84, respectively. This indicated that the available Cd and the biomass of Sedum alfredii were important factors in improving the phytoremediation efficiency using activators. The bioavailability of soil heavy metals was determined to be a crucial factor in the amount of heavy metals absorbed by plants(Xueying et al. 2019). Plants with larger biomass were found to accumulate more heavy metals in their roots and stems, thereby increasing the soil Cd removal rate.

The initial pH of the test soil was 7.63, and after applying different combinations of chemical reagents, the pH of the treated soils ranged from 7.40 to 7.70, showing no significant changes. It could be attributed to the soil used in the experiment as it was alkaline with inherent buffering capacity Besides, soil pH could be influenced not only by potassium fertilizers and organic acids but also by other environmental factors in the farmland, such as microorganisms, flora, and fauna. The pH had no significant impact on Cd removal and the growth of Sedum alfredii, with correlation coefficients of 0.25 and 0.15.

Conclusion

The available Cd content in the soil and the biomass of Sedum alfredii were increased by the addition of activators, raising the average Cd removal rate from 4.82–16.82%. The biomass of Sedum alfredii and its Cd removal rate were significantly increased by the application of organic acids CA and MA alone, with CA and MA enhancing the Cd removal rate to 25.98% and 21.36%, respectively, which was higher than previously reported in pot experiments. The remediation effect in Cd-contaminated soil by Sedum alfredii was greatly enhanced by CA and MA. PASP was found to be the most effective activator, increasing the available Cd by 14% without affecting the mobility and accumulation of Cd in the soil. Although the application of activators showed great potential in phytoremediation, it might increase the risk of heavy metals migrating into groundwater(Chen &Cutright 2001). Therefore, it is important to balance the remediation effect and preserving groundwater when choosing activators.

Declarations

Ethics approval

Not applicable.

Consent to participate

The authors all agree to participate in the paper.

Consent for publication

The authors all agree that the paper is published in the journal.

Competing interests

The authors declare no competing interests.

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Author contribution

Honggang Li:softwaredata□curation□investigation□writing-original draft□writing.Huang Ling: data curation and investigation□data collation and research, writing-review and editing.Qianjun Liu: writing-review and editing. Zhiliang Chen: project management, validation, funding acquisition, review and editing. Haochao Li and Xiaoqing Huang: Software.Wei Hang□Mengqaing Sun□data curation and investigation

Data Availability

All the authors declare that data will be made available on request.

References

1. Afshan S, Ali S, Bharwana SA, Rizwan M, Farid M, Abbas F, Ibrahim M, Mehmood MA, Abbasi GH (2015): Citric acid enhances the phytoextraction of chromium, plant growth, and photosynthesis by alleviating the oxidative damages in Brassica napusL. Environmental Science and Pollution Research 22, 11679-11689 http://dx.doi.org/10.1007/s11356-015-4396-8
2. Alozie N, Heaney N, Lin C (2018): Biochar immobilizes soil-borne arsenic but not cationic metals in the presence of low-molecular-weight organic acids. Science of the Total Environment 630, 1188-1194 http://dx.doi.org/10.1016/j.scitotenv.2018.02.319
3. Barrutia O, Garbisu C, Hernandez-Allica J, Ignacio Garcia-Plazaola J, Maria Becerril J (2010): Differences in EDTA-assisted metal phytoextraction between metallicolous and non-metallicolous accessions of Rumex acetosa L. Environmental Pollution 158, 1710-1715 http://dx.doi.org/10.1016/j.envpol.2009.11.027
4. Chao D, Qiang L, jian H (2023): Application of Sedum alfredii Hance in the remedition of Cd comtaminated farmland in the fields. Journal of Geology, (in Chinese)
5. Chen H, Cutright T (2001): EDTA and HEDTA effects on Cd, Cr, and Ni uptake by Helianthus annuus. Chemosphere 45, 21-28 http://dx.doi.org/10.1016/s0045-6535(01)00031-5
6. Chi G, Fang Y, Zhu B, Guo N, Chen X (2024): Intercropping with Brassica juncea L. enhances maize yield and promotes phytoremediation of cadmium-contaminated soil by changing rhizosphere properties. Journal of Hazardous Materials 461http://dx.doi.org/10.1016/j.jhazmat.2023.132727
7. Dou X, Dai H, Wei S, Hu Y, Skuza L (2019): Effects of Some Chelators and Surfactants on Hyperacculator Sedum alfredii Hance Remediating Contaminated Soil. Soil & Sediment Contamination 28, 747-756 http://dx.doi.org/10.1080/15320383.2019.1661352

8. Du S, Lu Q, Liu L, Wang Y, Li J (2022): Rhodococcus qingshengii facilitates the phytoextraction of Zn, Cd, Ni, and Pb from soils by Sedum alfredii Hance. Journal of Hazardous Materials 424http://dx.doi.org/10.1016/j.jhazmat.2021.127638
9. Farid M, Ali S, Rizwan M, Ali Q, Saeed R, Nasir T, Abbasi GH, Rehmani MIA, Ata-Ul-Karim ST, Bukhari SAH, Ahmad T (2018): Phyto-management of chromium contaminated soils through sunflower under exogenously applied 5-aminolevulinic acid. Ecotoxicology and Environmental Safety 151, 255-265 http://dx.doi.org/10.1016/j.ecoenv.2018.01.017
10. Fu R, Wen D, Xia X, Zhang W, Gu Y (2017): Electrokinetic remediation of chromium (Cr)-contaminated soil with citric acid (CA) and polyaspartic acid (PASP) as electrolytes. Chemical Engineering Journal 316, 601-608 http://dx.doi.org/10.1016/j.cej.2017.01.092
11. Gill SS, Khan NA, Tuteja N (2011): Differential cadmium stress tolerance in five indian mustard (Brassica juncea L.) cultivars: an evaluation of the role of antioxidant machinery. Plant signaling & behavior 6, 293-300
12. Guo X, Zhang G, Wei Z, Zhang L, He Q, Wu Q, Qian T (2018): Mixed chelators of EDTA, GLDA, and citric acid as washing agent effectively remove Cd, Zn, Pb, and Cu from soils. Journal of Soils and Sediments 18, 835-844 http://dx.doi.org/10.1007/s11368-017-1781-6
13. Hawrylak-Nowak B, Dresler S, Matraszek R (2015): Exogenous malic and acetic acids reduce cadmium phytotoxicity and enhance cadmium accumulation in roots of sunflower plants. Plant Physiology and Biochemistry 94, 225-234
14. He X, Zhang J, Ren Y, Sun C, Deng X, Qian M, Hu Z, Li R, Chen Y, Shen Z, Xia Y (2019): Polyaspartate and liquid amino acid fertilizer are appropriate alternatives for promoting the phytoextraction of cadmium and lead in Solanum nigrum L. Chemosphere 237http://dx.doi.org/10.1016/j.chemosphere.2019.124483
15. Hong-li F, WX, Wei Z (2008): Effect of malic acid and citric acid addition on Cd transfor mations in soil and Cd uptake in amaranth. Plant Nutrition and Fertilizer Science 14, 1132-138.(in Chinese)
16. Hu M-m, Dou Q-h, Cui X-m, Lou Y-h, Zhuge Y-p (2019): Polyaspartic acid mediates the absorption and translocation of mineral elements in tomato seedlings under combined copper and cadmium stress. Journal of Integrative Agriculture 18, 1130-1137 http://dx.doi.org/10.1016/s2095-3119(18)62017-9
17. Hui G, Jing-jing Z (2021): Effect of Exogenous Citric Acid Addition on emediation of Pb Contaminated Soil by Three Ornamental Plants. Southwest China Journal of Agricultural Sciences 34, 137-143.(in Chinese) http://dx.doi.org/10.16213/j.cnki.scjas.2021.1.021
18. Jez E, Lestan D (2016): EDTA retention and emissions from remediated soil. Chemosphere 151, 202-209 http://dx.doi.org/10.1016/j.chemosphere.2016.02.088
19. Jiang HX, Zhu J, Li KL, Liu WG, Wang P, Zhang K (2022): Exploring a library of water-soluble polymers as abiotic phytoremediation agents for treating (Pseudo)metal ion-contaminated soil. Chemosphere 289http://dx.doi.org/10.1016/j.chemosphere.2021.133261
20. Jin L, Xian-qiang Y, Hui-min S, Jia-long, Ge-hong W (2015): EDTA and EDDS Enhanced Remediation of Cd and Pb Contaminated Soil by Ramie Boehmeria Nivea . Journal of Agro-Environment Science

34, 293-1300.(in Chinese) http://dx.doi.org/10.11654/jaes.2015.07.010

21. Jing A, Xiao-shuang G, Shu-he W (2015): Research progress on technologies of phytoremediation of heavy metal contaminated soils. Chinese Journal of Ecology 34, 3261-3270(in Chinese) http://dx.doi.org/10.13292/j.1000-4890.20151023.025
22. Kan-qi L, Jia-ling W, Zhe C, Mao-lin L, Hong-yan Z (2023): Effects of natural organic acids on cadmium uptake by Sedum plumbizincicola from the soil. China Environmental Science 43, 2413-2422.(in Chinese) http://dx.doi.org/10.19674/j.cnki.issn1000-6923.20230110.005
23. Lee J, Sung K (2014): Effects of chelates on soil microbial properties, plant growth and heavy metal accumulation in plants. Ecological Engineering 73, 386-394 http://dx.doi.org/10.1016/j.ecoleng.2014.09.053
24. Li-wei C, Hai-ying C (2020): Comparative study on speciation of Cu□Pb and Zn from mining tailingsvia Tessier 5-step sequential extraction and improved BCR method. Journal of Safety and Environment, 735-740.(in Chinses) http://dx.doi.org/10.13637/j.issn.1009-6094.2019.0661
25. Li C, Yu F, Li Y, Niu W, Li J, Yang J, Liu K (2020): Comparative analysis of the seed germination of pakchoi and its phytoremediation efficacy combined with chemical amendment in four polluted soils. International Journal of Phytoremediation 22, 1156-1167 http://dx.doi.org/10.1080/15226514.2020.1741508
26. Li X, Tian L, Li B, Chen H, Zhao G, Qin X, Liu Y, Yang Y, Xu J (2023): Polyaspartic acid enhances the Cd phytoextraction efficiency of Bidens pilosa by remolding the rhizospheric environment and reprogramming plant metabolism. Chemosphere 312http://dx.doi.org/10.1016/j.chemosphere.2022.137242
27. Liang Y, Zhou C, Guo Z, Huang Z, Peng C, Zeng P, Xiao X, Xian Z (2019): Removal of cadmium, lead, and zinc from multi-metal-contaminated soil using chelate-assisted Sedum alfredii Hance. Environmental Science and Pollution Research 26, 28319-28327 http://dx.doi.org/10.1007/s11356-019-06041-w
28. Lin D, Juanjuan Z, Tanchun X, Xiaolin W, Ying Y (2021): Effects of citric acid on the bioavailability of Cd-pyrene contamination in soil-willow system. Journal of Nanjing University(Natural Science) 57, 375-384.(in Chinese) http://dx.doi.org/10.13232/j.cnki.jnju.2021.03.004
29. Liu D, Islam E, Li T, Yang X, Jin X, Mahmood Q (2008): Comparison of synthetic chelators and low molecular weight organic acids in enhancing phytoextraction of heavy metals by two ecotypes of Sedum alfredii Hance. Journal of Hazardous Materials 153, 114-122 http://dx.doi.org/10.1016/j.jhazmat.2007.08.026
30. Liu Y, Zhou J, Sun D, Chen H, Qin J, Chen G, Qiu R (2023): Polyaspartic acid assisted-phytoremediation of cadmium-contaminated farmland: Phytoextraction efficiency, soil quality, and rhizosphere microbial community. Science of the Total Environment 862http://dx.doi.org/10.1016/j.scitotenv.2022.160736
31. Mahar A, Wang P, Ali A, Awasthi MK, Lahori AH, Wang Q, Li R, Zhang Z (2016): Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. Ecotoxicology

and Environmental Safety 126, 111-121 http://dx.doi.org/10.1016/j.ecoenv.2015.12.023

32. Na L, Yu X, Xu-wen H, Lian-hua Y, Wei-jia L, Chang-jun H, Kai-yu X (2021): Research Progress of Cd Form Transformation and the Effective Environmental Factors in Soil Based on Tessier Analysis. Chinese Journal of Soil Science 52, 1505-1512.(in Chinese) http://dx.doi.org/10.19336/j.cnki.trtb.2020111101
33. Nardi S, Concheri G, Pizzeghello D, Sturaro A, Rella R, Parvoli G (2000): Soil organic matter mobilization by root exudates. Chemosphere 41, 653-658
34. Nawaz H, Asghar N, Ali A, Ameer A, Shehzad MA, Nawaz F, Mehmood A, Iqbal MS, Iqbal U, Kaleem M, Khan A, Ahmad KS (2023): Optimization of Citric Acid and EDTA Levels Under Ni Stress Using Rapeseed Brassica napus L. for Phytoremediation. Water Air and Soil Pollution 234http://dx.doi.org/10.1007/s11270-023-06229-4
35. Nevel LV, Mertens J, Oorts K, Verheyen K (2007): Phytoextraction of metals from soils: How far from practice? Environmental Pollution 150, 34-40
36. R ZY, Z HY (2023): Effects of chelating agents and organic acids on remediation of cadmium and arsenic complex contaminated farmland by Phytolacca acinosa Roxb. Journal of Agro□Environment Science 42, 1936-1944.(in Chinese) http://dx.doi.org/10.11654/jaes.2022-0510
37. Shahid M, Austruy A, Echevarria G, Arshad M, Sanaullah M, Aslam M, Nadeem M, Nasim W, Dumat C (2014): EDTA-Enhanced Phytoremediation of Heavy Metals: A Review. Soil & Sediment Contamination 23, 389-416 http://dx.doi.org/10.1080/15320383.2014.831029
38. Song J, Ma R, Huang W, Yang D, Cui X (2014): EXOGENOUS ORGANIC ACIDS PROTECT CHANGBAI LARCH (LARIX OLGENSIS) SEEDLINGS AGAINST CADMIUM TOXICITY. Fresenius Environmental Bulletin 23, 3460-3468
39. Stojanov N, Maletic S, Beljin J, Dukanovic N, Kiprovski B, Zeremski T (2024): Enhancing Phytoextraction Potential of Brassica napus for Contaminated Dredged Sediment Using Nitrogen Fertilizers and Organic Acids. Plants-Basel 13http://dx.doi.org/10.3390/plants13060818
40. Sun Y-b, Zhou Q-x, An J, Liu W-t, Liu R (2009): Chelator-enhanced phytoextraction of heavy metals from contaminated soil irrigated by industrial wastewater with the hyperaccumulator plant (Sedum alfredii Hance). Geoderma 150, 106-112 http://dx.doi.org/10.1016/j.geoderma.2009.01.016
41. Teng Y, Li Z, Yu A, Guan W, Wang Z, Yu H, Zou L (2022): Phytoremediation of cadmium-contaminated soils by Solanum nigrum L. enhanced with biodegradable chelating agents. Environmental Science and Pollution Research 29, 56750-56759 http://dx.doi.org/10.1007/s11356-022-19879-4
42. Turgut C, Pepe MK, Cutright TJ (2004): The effect of EDTA and citric acid on phytoremediation of Cd, Cr, and Ni from soil using Helianthus annuus. Environmental Pollution 131, 147-154 http://dx.doi.org/10.1016/j.envpol.2004.01.017
43. Wang Y, Li S, Wang X, Xu J, Li T, Zhu J, Yang R, Wang J, Chang M, Wang L (2021): Biochelator Assisted Phytoremediation for Cadmium (Cd) Pollution in Paddy Field. Sustainability 13http://dx.doi.org/10.3390/su132112170

44. Wu X, Tian H, Li L, Wang X (2021): Polyaspartic acid alleviates cadmium toxicity in rapeseed leaves by affecting cadmium translocation and cell wall fixation of cadmium. Ecotoxicology and Environmental Safety 224http://dx.doi.org/10.1016/j.ecoenv.2021.112685
45. Xiaojuan W, Wenbin W, Long Y, Liang J, Yu S, Shaojun J, Lanlan Q (2015): Transport pathways of cadmium (Cd) and its regulatory mechanisms in plant. ACTA ECOLOGICA SINICA 35, 7921-7929.(in Chinese) http://dx.doi.org/10.5846 /stxb201404170754
46. Xin-yu G, Cun-wei K, Er-jiang M, Xiao-yao W, Shi-li Q, Li-di G (2023): Enhanced phytoremediation of Cd-contaminated soil with Amaranthus Hypochondriacus L. by polyaspartic acid. Journal of Qiqihar University(Natural Science Edition) 39, 68-73.(in Chinese)
47. Xueying C, Changyin T, Yucheng X, Bing D, Shangyou Z, Yizhi W (2019): Effect of Soil pH and Total Cadmium Concentration of Soil on the emediation Efficiency of Sedum plumbizincicola. esearch of Environmental Sciences 32, 1604-1612.(in Chinese) http://dx.doi.org/10.13198/j.issn.1001-6929.2019.05.08
48. Yang, Liu, Liu, Zhang, Zhai, Liu, Wang, Chen, Chen, Wang (2019): Biodegradable PASP can effectively inhibit nitrification, moderate NH3 emission, and promote crop yield. Archives of Agronomy and Soil Science 65, 1273-1286
49. Yang Q, Yang C, Yu H, Zhao Z, Bai Z (2021): The addition of degradable chelating agents enhances maize phytoremediation efficiency in Cd-contaminated soils. Chemosphere 269http://dx.doi.org/10.1016/j.chemosphere.2020.129373
50. Yifeng F, Yuyang Z (2008): Removal of heavy metals from contaminated soil with biodegradable chelating agents-polyaspartic acid. Ecology and Environment 17, 237-240.(in Chinese) http://dx.doi.org/10.16258/j.cnki.1674-5906.2008.01.044
51. Yu G, Jiang P, Fu X, Liu J, Sunahara GI, Chen Z, Xiao H, Lin F, Wang X (2020): Phytoextraction of cadmium-contaminated soil by Celosia argentea Linn.: A long-term field study. Environmental Pollution 266http://dx.doi.org/10.1016/j.envpol.2020.115408
52. Zaheer IE, Ali S, Rizwan M, Farid M, Shakoor MB, Gill RA, Najeeb U, Iqbal N, Ahmad R (2015): Citric acid assisted phytoremediation of copper by Brassica napus L. Ecotoxicology and Environmental Safety 120, 310-317
53. Zaier H, Ghnaya T, Ben Rejeb K, Lakhdar A, Rejeb S, Jemal F (2010): Effects of EDTA on phytoextraction of heavy metals (Zn, Mn and Pb) from sludge-amended soil with Brassica napus. Bioresource Technology 101, 3978-3983 http://dx.doi.org/10.1016/j.biortech.2010.01.035
54. Zhang S, Chen H, He D, He X, Yan Y, Wu K, Wei H (2020): Effects of Exogenous Organic Acids on Cd Tolerance Mechanism of Salix variegata Franch. Under Cd Stress. Frontiers in Plant Science 11http://dx.doi.org/10.3389/fpls.2020.594352
55. Zhang Y, Li F, Xu W, Ren J, Chen S, Shen K, Long Z (2019): Enhanced Phytoextraction for Co-contaminated Soil with Cd and Pb by Ryegrass (Lolium perenne L.). Bulletin of Environmental Contamination and Toxicology 103, 147-154 http://dx.doi.org/10.1007/s00128-019-02661-7

56. Zhi-guo F, Jun-ting X, Qing Y, Ye-zhen L, Hai H, Yun-xian Z, Si-min Y, Xin-tao W □ole and Mechanism of Low Molecular-Weight-Organic Acids in Enhanced Phytoremediation of Heavy Metal Contaminated Soil. Environmental Science 43, 4669-4678.(in Chinese) http://dx.doi.org/10.13227/j.hjkx.202201062
57. zhu XM-i, Zhong-ke B, Zhong-qiu Z (2008): Advances on the study of chelate-enhanced phytoremediation for heavy metal contaminated soils. Soil and Fertilizer Sciences in China 1, 6-11(in Chinese)

Table

Table 1 is available in the Supplementary Files section.

Figures

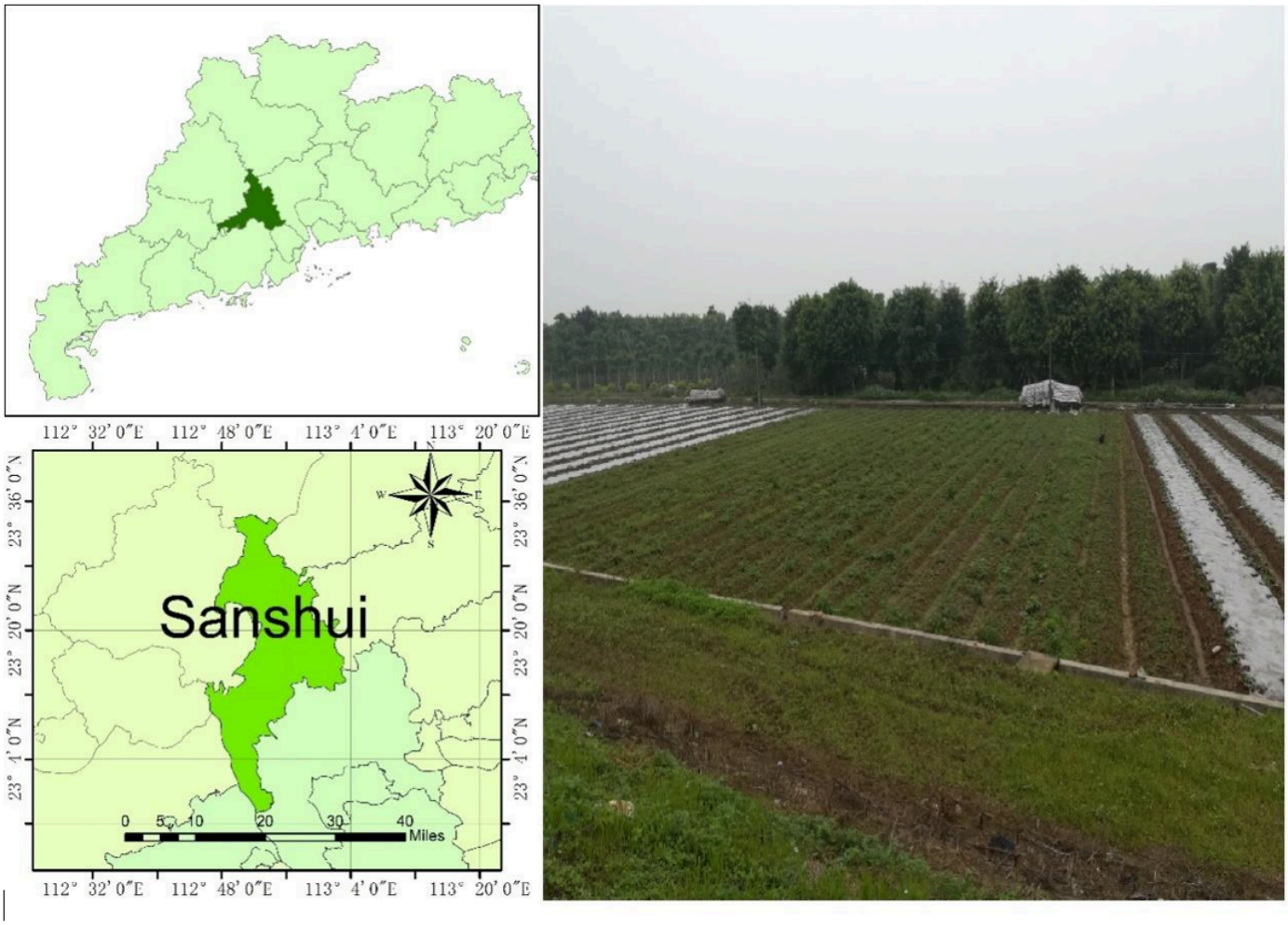


Figure 1

Summary map

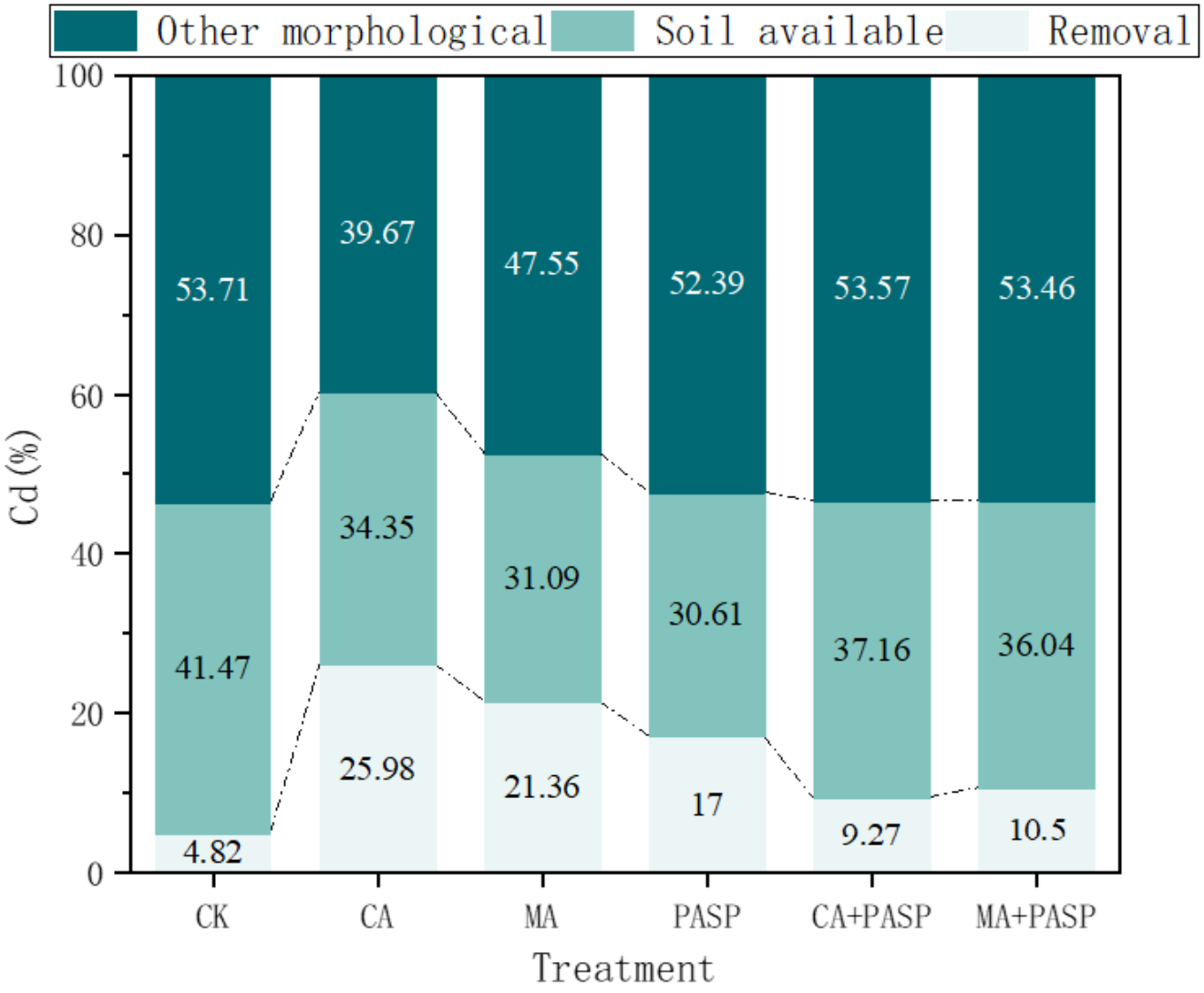


Figure 2

Removal and activation rates of Soil Cd

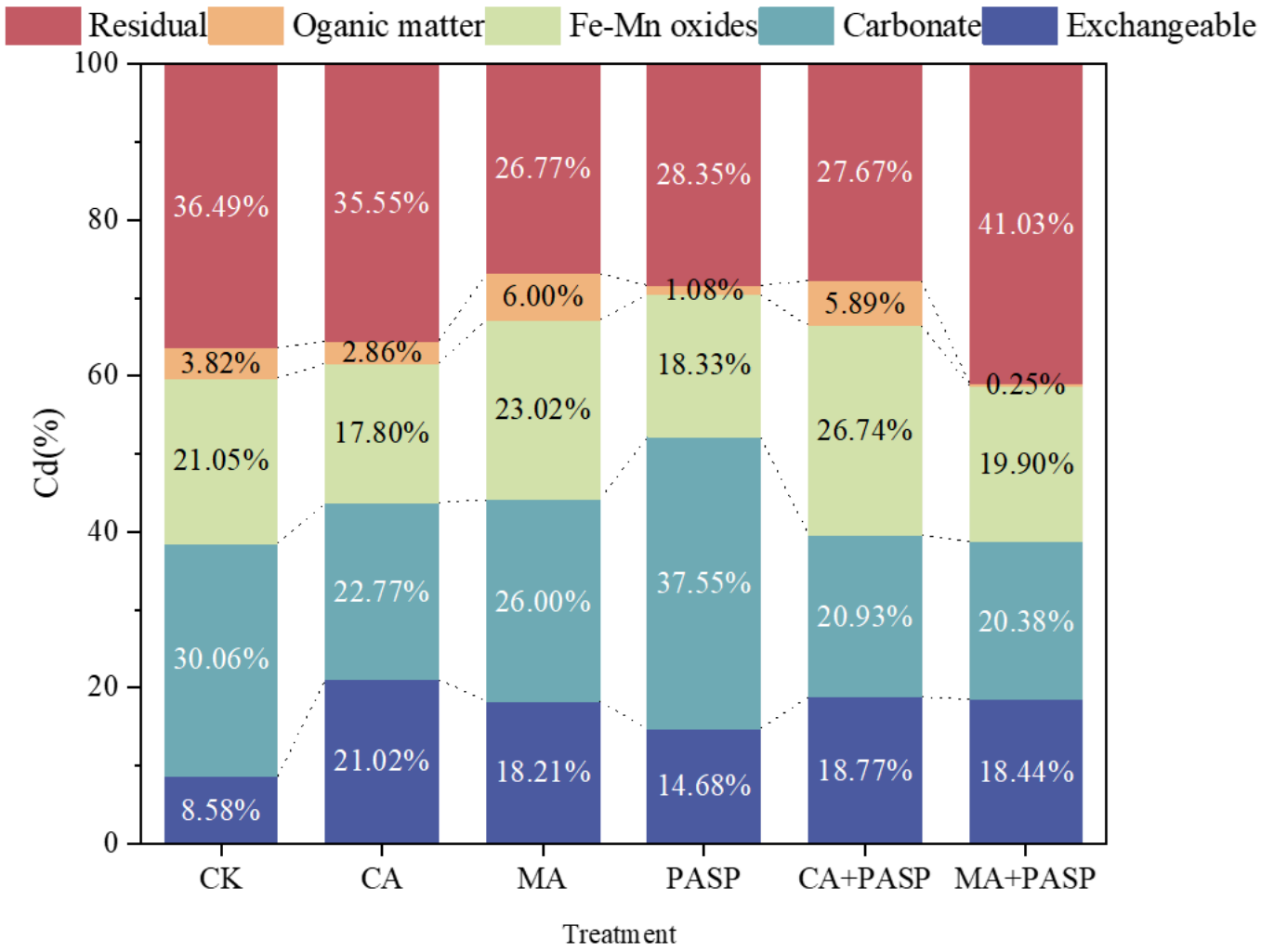


Figure 3

Morphological distribution of Cd after treatment

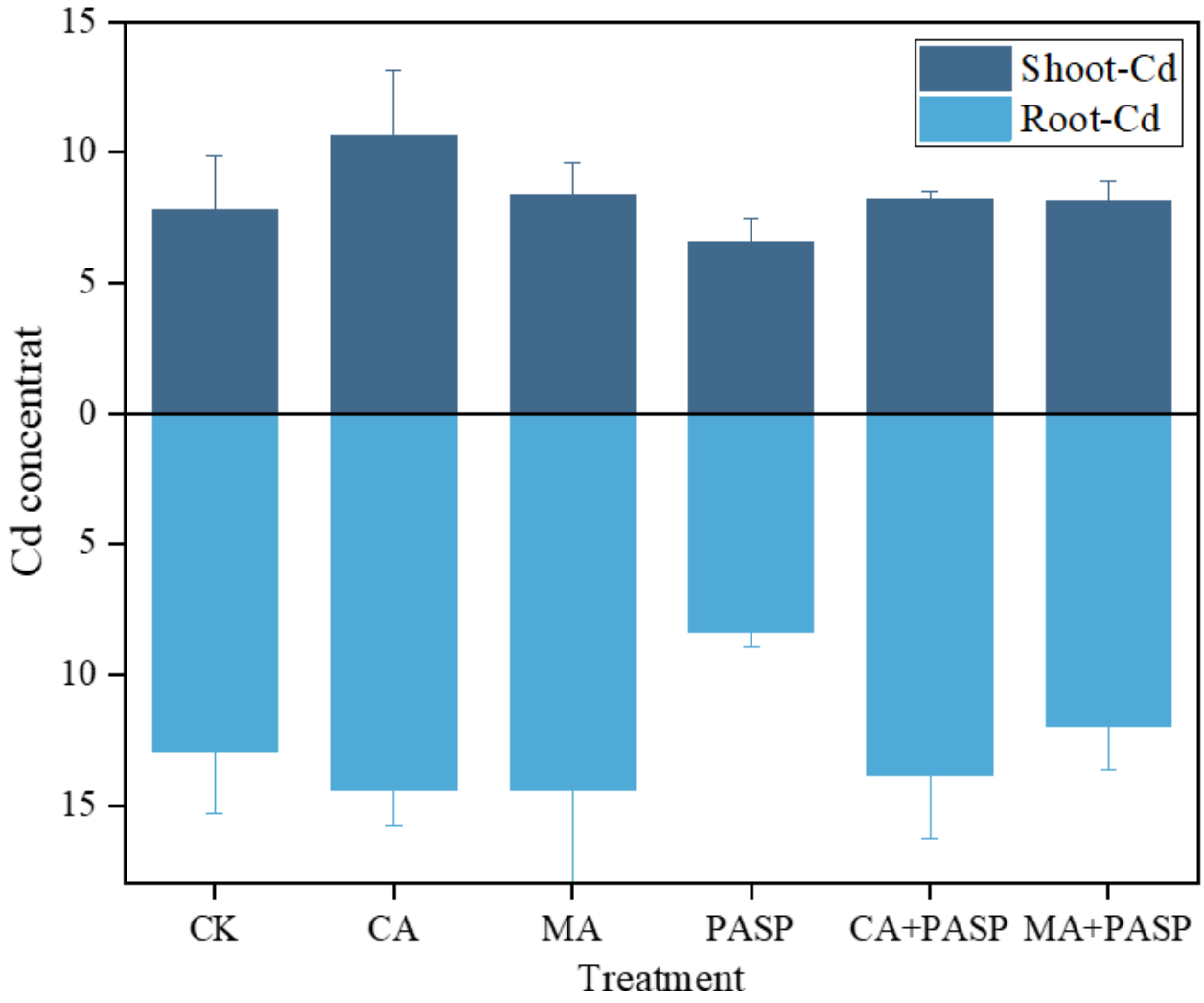


Figure 4

Cd concentration in the shoots and roots of Sedum alfredii

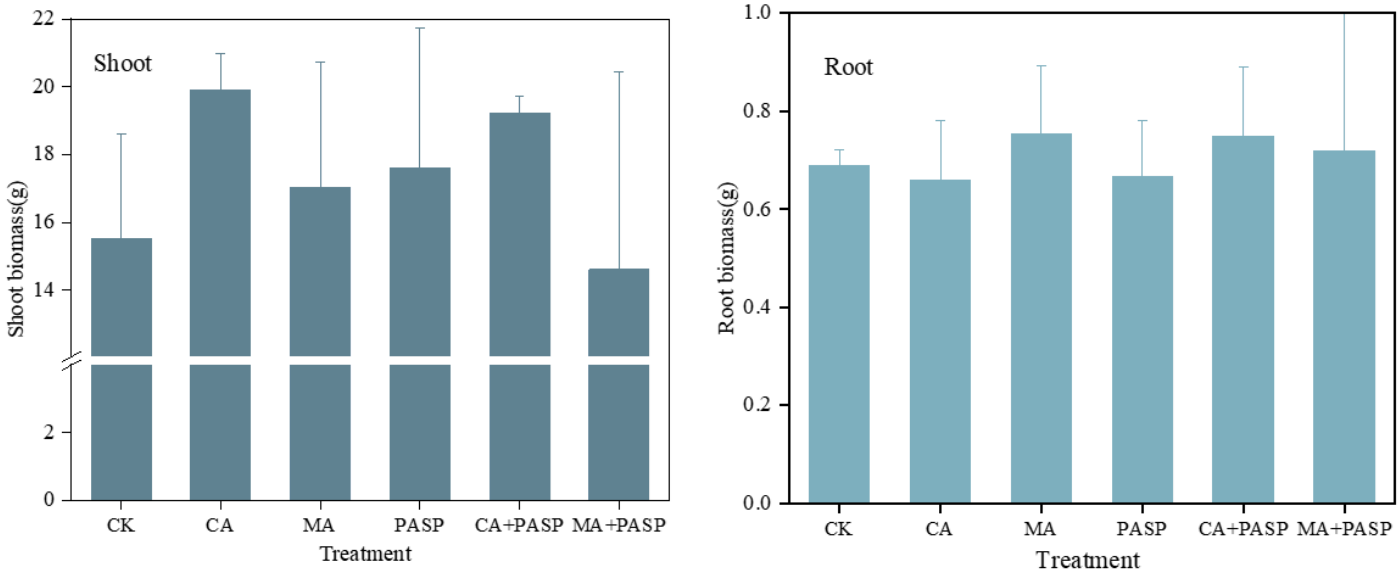


Figure 5

Biomass of shoots and roots of Sedum alfredii

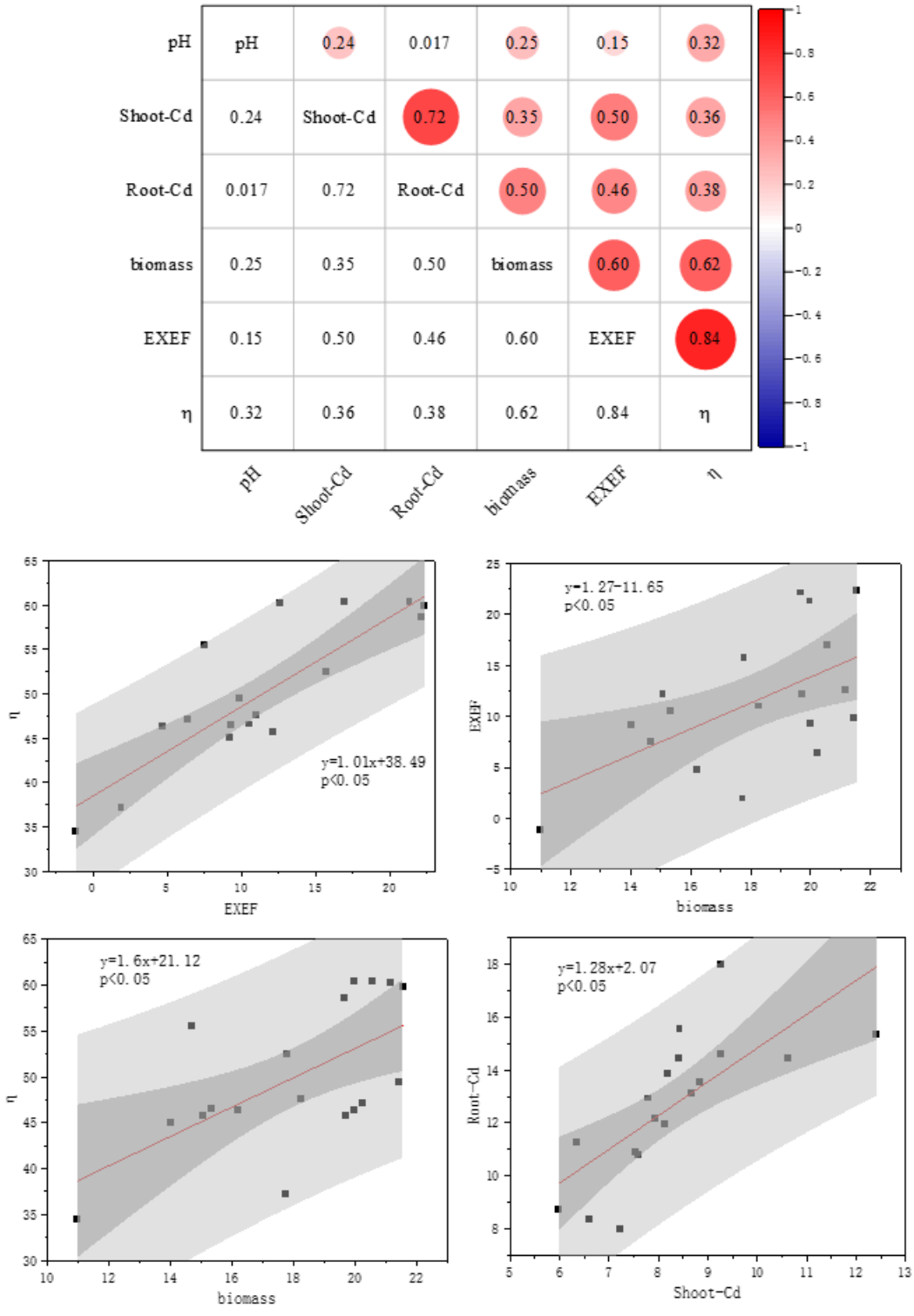


Figure 6

Correlation Relationship Diagram

Supplementary Files

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- Table1.docx