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Effect of AC electric field on enhancing phytoremediation of Cd-contaminated soils in different pH soils

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To increase the efficiency of phytoremediation to clean up heavy metals in soil, assisted with alternating current (AC) electric field technology is a promising choice. Our experiments utilized the hyperaccumulator Sedum alfredii Hance and the fast-growing, high-biomass willow (*Salix* sp.). We investigated the efficiency of AC field combined with *S. alfredii*—willow intercropping for removing Cd from soils with different pH values. In the AC electric field treatment with *S. alfredii*—willow intercropping, the available Cd content in acidic soil increased by 50.00% compared to the control, and in alkaline soil, the increase was 100.00%. Furthermore, AC electric field promoted Cd uptake by plants in both acidic and alkaline soils, with Cd accumulation in the aboveground increased by 20.52% ($P < 0.05$) and 11.73%, respectively. In conclusion, the integration of AC electric fields with phytoremediation demonstrates significant favorable effectiveness.

Keywords AC electric field, Phytoremediation, *Sedum alfredii* Hance, Willow (*Salix* sp.), Cd contaminated soil, pH

Soil heavy metal pollution in agricultural land is of great concern due to its risk to safe food production and human health. Cadmium (Cd) is particularly problematic because of its toxicity and prevalence, especially in countries like China. To clean up the farmland soil heavy metals is a tough task and its efficient remediation remains a great challenge. Phytoremediation is considered a promising approach to addressing soil Cd pollution due to its cost-effectiveness and safety[1]. Hyperaccumulators such as *S. alfredii* have the capacity to accumulate high levels of toxic heavy metals in their tissues, efficiently absorbing various harmful metals from the soil[2,3]. The potential phytoaccumulation of Cd in *S. alfredii* can reach up to 11,000 mg kg^{-1} in leaves, 5300 mg kg^{-1} in stems, and 3100 mg kg^{-1} in roots[4].

Soil pH significantly influences the extraction of essential nutrients and heavy metals by plants[5]. It is one of the most critical factors affecting Cd uptake, as seen in plants like *Bidens pilosa L*[6–8]. The efficiency of phytoremediation is primarily influenced by plant biomass and the rate of contaminant uptake[1]. The combined application of electro-remediation and phytoremediation has been found to enhance the efficiency of remediating heavy metal-contaminated soil in crops like rapeseed (*Brassica napus*) and tobacco (*Nicotiana tabacum*)[9]. AC electric fields can stimulate cells and promote plant growth[10–12]. For instance, the biomass of lettuce (*Lactuca sativa*) and potato tubers was higher under AC electric field treatment, along with increased heavy metal content in the plants[13–15]. AC electric fields increase the bioavailability of heavy metals in soil by stimulating the movement of water and ions. The movement of water and ions in the soil facilitates the transport of heavy metals to plant roots and the subsequent translocation from roots to aboveground tissues. This overall improvement enhances the efficiency of phytoremediation in heavy metal-contaminated soils[16,17].

Previous studies have reported that fertilizer application and plant cultivation patterns affect the effect of AC electric fields. Whereas the soils used in the previous work were all acidic, as effects of different fertilizer treatments on AC electric field–assisted phytoremediation efficiency of Cd-contaminated soil by willow and *S. alfredii*[18,19]. To further improve the phytoremediation efficiency, this experiment hypothesized that soil properties

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and plant growth under the AC electric field combined with *S. alfredii*—willow intercropping were affected by soil acidity and alkalinity, and soil heavy metal remediation efficiency was changed accordingly. We designed a pot experiment to investigate the effects of AC electric field and soil pH on the Cd removal efficiency of *S. alfredii*—willow intercropping.

Materials and methods
Materials
The test soils used in this study were contaminated with Cd and obtained from the surface layer at a depth of 0–20 cm. Soil A, characterized by its acidity, was sourced from the experimental base of the Academy of Agricultural Sciences in Wenzhou City, Zhejiang Province. Soil B, exhibiting alkaline properties, was collected from the experimental premises of the Academy of Agricultural Sciences in Foshan City, Guangdong Province. Prior to testing, the soil samples were air-dried and ground to pass through a 5 mm sieve for use in pot experiments. The fundamental characteristics of the examined soils are outlined in Table 1.

S. alfredii, a Cd hyperaccumulator, was obtained from an old lead–zinc mine in Quzhou City, Zhejiang Province. After cultivation at the experimental base of Zhejiang A & F University, plant cuttings of uniform size, approximately 5 cm in length with terminal buds removed, were selected as test materials. Willow No.3, sourced from Minshi horticulture in Suqian, Jiangsu Province, was also utilized. Willow cuttings approximately 15 cm in length, exhibiting healthy growth and similar sizes, were carefully washed with ultra-pure water before use.

Experimental design and treatments
The healthy and uniform cuttings of willow and *S. alfredii* cuttings were transplanted into plastic pots (202 mm top diameter, 198 mm height, 170 mm base diameter). Each pot contained 4 kg of either soil A or soil B. The willow cuttings were spaced 3 cm apart, while the *S. alfredii* cuttings were spaced 5 cm apart. Graphite sticks (10 mm diameter*100 mm length) were inserted on both sides of the pots and connected to a voltage regulator (model: TDGC2-0.5KVA), establishing an AC voltage intensity gradient of either 0 or 0.5 V cm^{-1}. The experiment lasted for 2 months, with soil moisture maintained at 60% of the field water holding capacity. Each treatment was replicated three times. The details of the different experimental treatments are listed in Table 2. Plant and soil samples were collected at harvest.

Analyses of soil and plant samples
The analysis methods for soil and plant samples were referred to Bao[20]. Soil samples were air-dried, finely ground, and passed through 10 and 100-mesh sieves for analysis. The soil pH was measured using a pH meter (Sartorius, model PB-10, German) with a water to soil ratio of 1:2.5 (m/V). The soil organic carbon (SOC) content was analyzed with the potassium dichromate external heating method. Soil available nitrogen (AN) concentration was determined by the diffusion absorption method (soil samples were reacted with 1 mol L^{-1} NaOH, and the released NH_3 was absorbed by 0.3 mol L^{-1} H_3BO_3). Soil available potassium (AK) concentration was determined using the ammonium acetate extraction-flame photometry method. Soil available phosphorus (AP) concentration was determined by Olsen method (0.5 mol L^{-1} $NaHCO_3$ extraction—molybdenum blue colorimetric method). The total Cd concentration in the soil was determined by ICP-OES (Optima 7000DV, PerkinElmer Co., USA) after digestion with HF-$HClO_4$-HNO_3 (3:1:1). The soil available Cd was extracted using a DTPA solution and determined by ICP-OES.

Test soils	Soil A	Soil B
pH	6.30	7.73
SOC/(g kg^{-1})	24.07	11.33
Available N/(mg kg^{-1})	242.00	96.00
Available P/(mg kg^{-1})	72.30	21.00
Available K/(mg kg^{-1})	354.00	122.00
Total Cd/(mg kg^{-1})	2.47	3.43
Available Cd/(mg kg^{-1})	0.28	0.35

Table 1. Soils physico-chemical properties.

Treatments	AC electric field/(V cm^{-1})	Soil type
I	0	Soil A
II	0.5	Soil A
III	0	Soil B
IV	0.5	Soil B

Table 2. Experimental treatments.

The willow plants samples were divided into different parts, including leaves, branches, stems, and root systems. The *S. alfredii* plants were separated into aboveground shoots and underground roots. Fresh plant samples were thoroughly washed, and their fresh weights were recorded. The samples were dried at 70 ℃ until a constant weight was achieved, and their dry weights were recorded. After grinding, the plant samples were sieved through a 20-mesh sieve for analysis. The plant samples were digested with HNO_3. Concentrations of Cd in the solutions were analyzed by ICP-OES.

The quality assurance and quality control (QA/QC) of analyses were carried out by comparison with certified reference materials: GSS-4 for soil and GSV-2 for plants.

Data analysis

Analysis of variance (Duncan) was conducted using the SPSS 25.0 statistical package (IBM, USA). The data was visualized using ORIGIN 2021 software.

Statement

The study complies with relevant institutional, national, and international guidelines and legislation.

Results

Soil properties

The application of the AC electric field for two months did not cause significant alterations in both soil pH and SOC. By contrast, the soil AN, AP, and AK were consistently increased by the application of AC electric field across the two different soils, albeit with varying degrees of enhancement. Specifically, in the acidic soil, AC electric field (treatment II) led to 6.54%, 11.67% ($P < 0.05$), and 12.22% ($P < 0.05$) higher levels of AN, AP, and AK, respectively, compared to the control (treatment I). Similarly, in the alkaline soil, the AC electric field (treatment IV) resulted in 15.13%, 79.87% ($P < 0.05$), and 17.71% higher levels of exhibited levels of AN, AP, and AK, respectively, compared to the control (treatment III). The application of AC electric field also resulted in increase of the Cd availability of both soils. Cd availability increased by 50.00% ($p < 0.05$) in acidic soil under the influence of AC electric field (treatment II) as compared to control treatment (I). Similarly, in alkaline soil, the Cd availability increased by 100.00% ($P < 0.05$) under AC electric field (treatment IV) as compared to the control treatment (III) (Fig. 1).

Plant growth

Soil type had significant impact on both fresh weight and dry weight of various parts of the willow, while the application of an AC electric field had a more pronounced effect on plant shoot growth of *S. alfredii* than the root (Table 3). The interaction between soil type and AC electric field had a significant impact on the dry weight

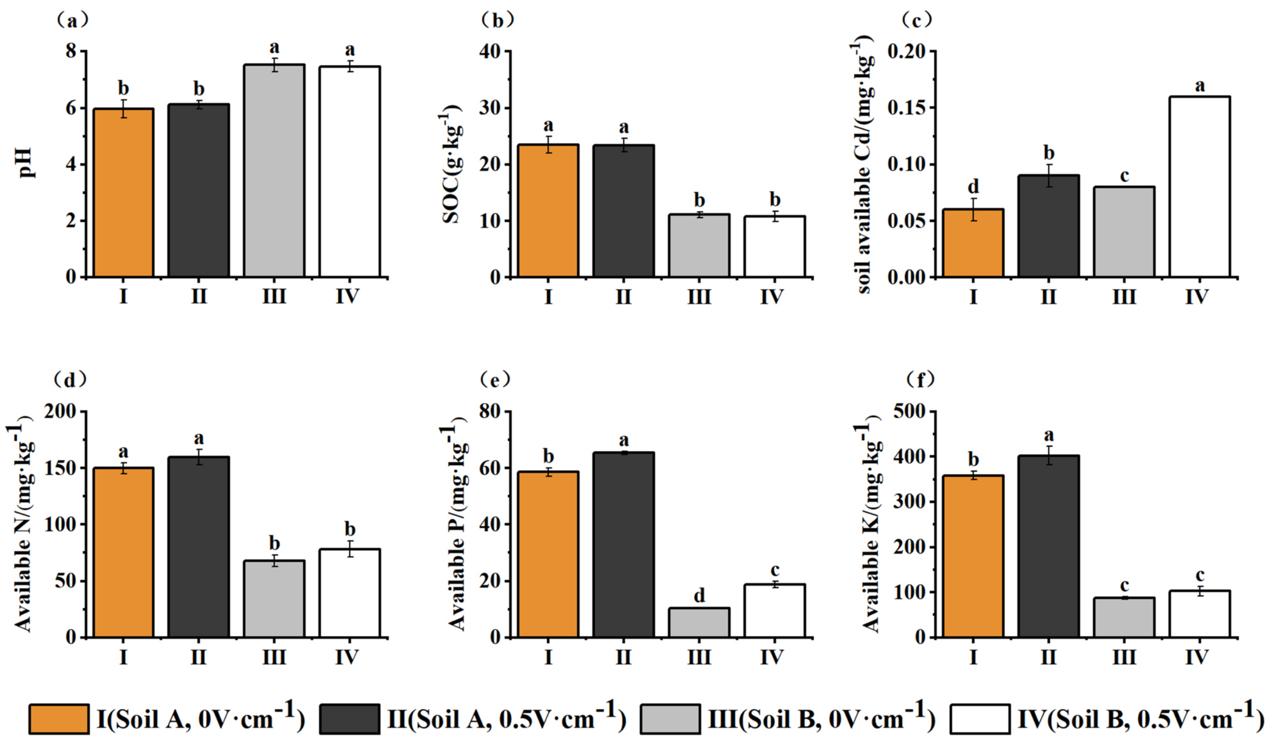

Figure 1. Effects of AC electric field on soil basic properties. Data in the figure are expressed as mean ± standard deviation of three replicates. Different letters above the columns indicate significant differences between different treatments determined by Duncan ($P < 0.05$).

	Soil type	AC electric field	Soil type * AC electric field
Willow leaf fresh weight	**	*	*
Willow leaf dry weight	**	ns	ns
Willow branches fresh weight	**	ns	ns
Willow branches dry weight	**	*	ns
Willow stem fresh weight	**	**	**
Willow stem dry weight	**	ns	**
Willow roots fresh weight	**	**	ns
Willow roots dry weight	**	**	*
Fresh weight in the aboveground parts of *S. alfredii*	*	*	ns
Dry weight in the aboveground parts of *S. alfredii*	ns	*	ns
Fresh weight in the underground parts of *S. alfredii*	**	ns	**
Dry weight in the underground parts of *S. alfredii*	ns	ns	ns
Cd accumulation in willows (shoots)	**	ns	ns
Cd accumulation in *S. alfredii* (shoots)	ns	**	ns
Total accumulation of Cd in shoots of the two plants	**	**	**

Table 3. Tests of between subjects effects between soil type and AC electric field. ANOVA, analysis of variance; ns, non-significant;*significant at $P < 0.05$, ** significant at $P < 0.01$.

of willow stem and the root fresh weight of *S. alfredii*. In acidic soil, the AC electric field significantly improved plant growth regardless of plant species (Table 4). In contrast, the effect was more noticeable on the growth of *S. alfredii* compared to willow in alkaline soil. Plant growth was generally much greater in acidic soil than in alkaline soil, and the growth of willow appeared to be more remarkably inhibited by high soil pH compared to *S. alfredii*.

In acidic soil, the dry weight of willow roots under AC electric field (treatment II) was significantly lower than that of the control treatment (I). The application of the AC electric field (treatment II) increased the dry weight of willow shoots, *S. alfredii* shoots and roots by 13.50% ($P < 0.05$), 59.09% ($P < 0.05$) and 125.00% ($P < 0.05$), respectively, when compared to the control (treatment I). However, in alkaline soil, the application of AC electric field (treatment IV) led to great decrease of willow dry weight by 89.96% but an increase in the dry weight of *S. alfredii* shoots by 40.00% compared to the control (treatment III). Nevertheless, the dry weights of willow and *S. alfredii* roots were lower than that of the control (treatment III).

Plant Cd concentrations

As illustrated in Fig. 2, the impact of the AC electric field on Cd concentrations in various parts of willow and *S. alfredii* appeared to be quite consistent across different soil types. The AC electric field treatment resulted in increased Cd concentrations in most plant parts, with the exception of willow branches. In the acidic soil (treatment II), Cd concentrations in willow leaves, willow stems, willow roots, the aboveground parts of *S. alfredii*, and the underground parts of *S. alfredii* showed significant increases of 17.21% ($P < 0.05$), 18.56% ($P < 0.05$), 9.40%, 34.89% ($P < 0.05$), and 4.85% ($P < 0.05$), respectively, when compared to the control (treatment I). In the alkaline soil treatment (IV) under the influence of the AC electric field, Cd concentrations in willow leaves, willow stem, willow roots, the aboveground part of *S. alfredii*, and the underground part of *S. alfredii* exhibited higher values compared to treatment III, with increased by 4.80%, 10.64%, 13.42%, 18.72% ($P < 0.05$), 7.99% ($P < 0.05$).

Plant Cd accumulation

From Fig. 3, it is evident that in the acidic soil, the accumulation of Cd in all parts of both willow and *S. alfredii* was significantly higher when subjected to the AC electric field (treatment II) compared to control (treatment I). Specifically, Cd accumulation in willow leaves, willow branches, willow stems, willow roots, the aboveground parts of *S. alfredii*, and underground parts of *S. alfredii* increased by 22.17%, 9.34%, 23.34%, 20.24% ($P < 0.05$), 159.91% ($P < 0.05$), and 90.73% ($P < 0.05$), respectively, compared to the control (treatment I). In addition, total

	Biomass of willow/(g plant^{-1})				Biomass of *S. alfredii* /(g plant^{-1})			
	Fresh weight		Dry weight		Fresh weight		Dry weight	
Treatment	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots
I (0 V cm^{-1})	17.59 ± 1.09b	6.12 ± 0.26a	8.30 ± 0.30b	1.05 ± 0.03a	3.95 ± 0.85a	0.52 ± 0.14b	0.22 ± 0.06b	0.04 ± 0.01a
II (0.5 V cm^{-1})	22.17 ± 0.36a	5.13 ± 0.14b	9.42 ± 0.23a	0.90 ± 0.07b	4.39 ± 0.34a	0.71 ± 0.03a	0.35 ± 0.07a	0.09 ± 0.02a
III (0 V cm^{-1})	14.39 ± 1.03c	3.25 ± 0.45c	7.37 ± 0.51c	0.73 ± 0.04c	2.66 ± 0.58b	0.36 ± 0.03c	0.20 ± 0.04b	0.08 ± 0.07a
IV (0.5 V cm^{-1})	14.65 ± 0.91c	2.53 ± 0.07d	6.63 ± 0.19d	0.41 ± 0.07d	3.88 ± 0.04a	0.23 ± 0.03d	0.28 ± 0.06ab	0.05 ± 0.03a

Table 4. Effects of soil type on growth of willow and *S. alfredii* under AC electric field.

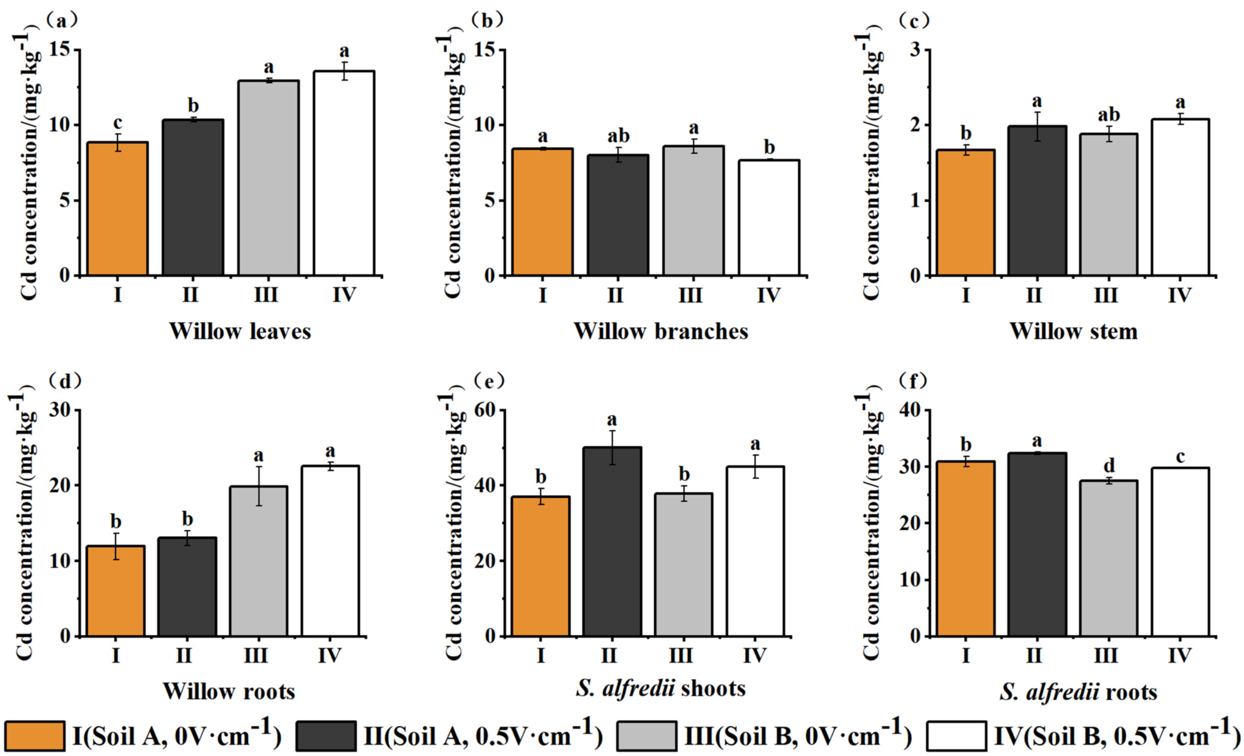

Figure 2. Effects of soil type on concentrations of Cd in willow and *S. alfredii* under AC electric field.

Cd accumulation in the aboveground parts of willow and the aboveground parts of both plants per pot (treatment II) significantly increased by 14.10% ($P < 0.05$) and 20.52% ($P < 0.05$), respectively, compared to the control (treatment I). Similarly, in the alkaline soil, Cd accumulation in willow leaves and the aboveground parts of *S. alfredii* was higher under the AC electric field (treatment IV) than in the control (treatment III), but the effect was much smaller than those in the acidic soil, showing increases of 24.60% and 65.84% ($P < 0.05$). By contrast, the Cd accumulation in willow branches, willow stems, willow roots, and the underground parts of *S. alfredii* was lower than that in the control (treatment III). However, in terms of total plant Cd accumulation, the total Cd accumulation in the aboveground parts of the willow and the total Cd accumulation in the aboveground parts of both plants per pot (treatment IV) increased by 0.08% and 11.73% ($P < 0.05$), respectively, compared to the control (treatment III).

Discussion

In our study, the AC electric field had a noticeable impact on soil available Cd (Fig. 1), potentially due to its activating effect on the soil heavy metals[21,22]. The application of an AC electric field enhances the activity of metal ions in the soil by converting bound and residual Cd into exchangeable forms. This process promotes the desorption of Cd from the soil surface into the soil solution, thereby enhancing the effectiveness and mobility of Cd in the soil[23]. Soil pH and SOC are crucial factors influencing the mobility and availability of Cd, with different soil properties significantly impacting the availability of soil heavy metals[24–26]. The higher the pH, the lower the Cd availability[5,6]. Increasing soil pH leads to more adsorption sites for positively charged metal ions ultimately decreasing soil available Cd concentration[27,28]. In contrast, lowering soil pH is favorable for soil to release free Cd cations[29]. SOC can influence the form and mobility of heavy metals in the soil and the dissolved organic matter increases Cd availability[30,31]. The AC electric field treatment has a limited impact on soil pH due to its periodic polarity reversal[9,32–34]. Our results also indicated that the AC electric field had minimal effects on pH and SOM levels (Fig. 1). AC electric fields can have an effect on soil microorganisms and plant root metabolism. The SOC may be affected by prolonging test[11,12]. However, other studies suggest that voltage at the inter-root level may affect denitrifying bacteria's conversion efficiency, impacting plant growth[35,36]. In addition, the AC electric field increased the availabilities of soil nutrients N, P, and K, which were favorable for plant growth. Soil nutrients such as nitrogen may be converted by hydrolysis into simple organic and inorganic nitrogen in electric fields, which are then redistributed in the soil. The electric field may modulate the metabolic actions of plants and soil microorganisms, enhancing the conversion of nitrogen, phosphorus, and potassium into plant-available forms[5,37].

Both the AC electric field and soil type exerted great significant influence on plant growth (Table 3). Previous research has shown that applying an electric field facilitates plant growth and biomass production, and this increase in biomass is not solely due to water storage in plant tissues[38]. In present study, the AC electric field treatment increased both fresh and dry weights of willow and *S. alfredii*, thereby promoting plant growth, in line with earlier studies[18,39]. The impact of the electric field stimulated cell division and differentiation, accelerated root metabolism, and promoted root growth. With increased root growth, nutrients were transported more

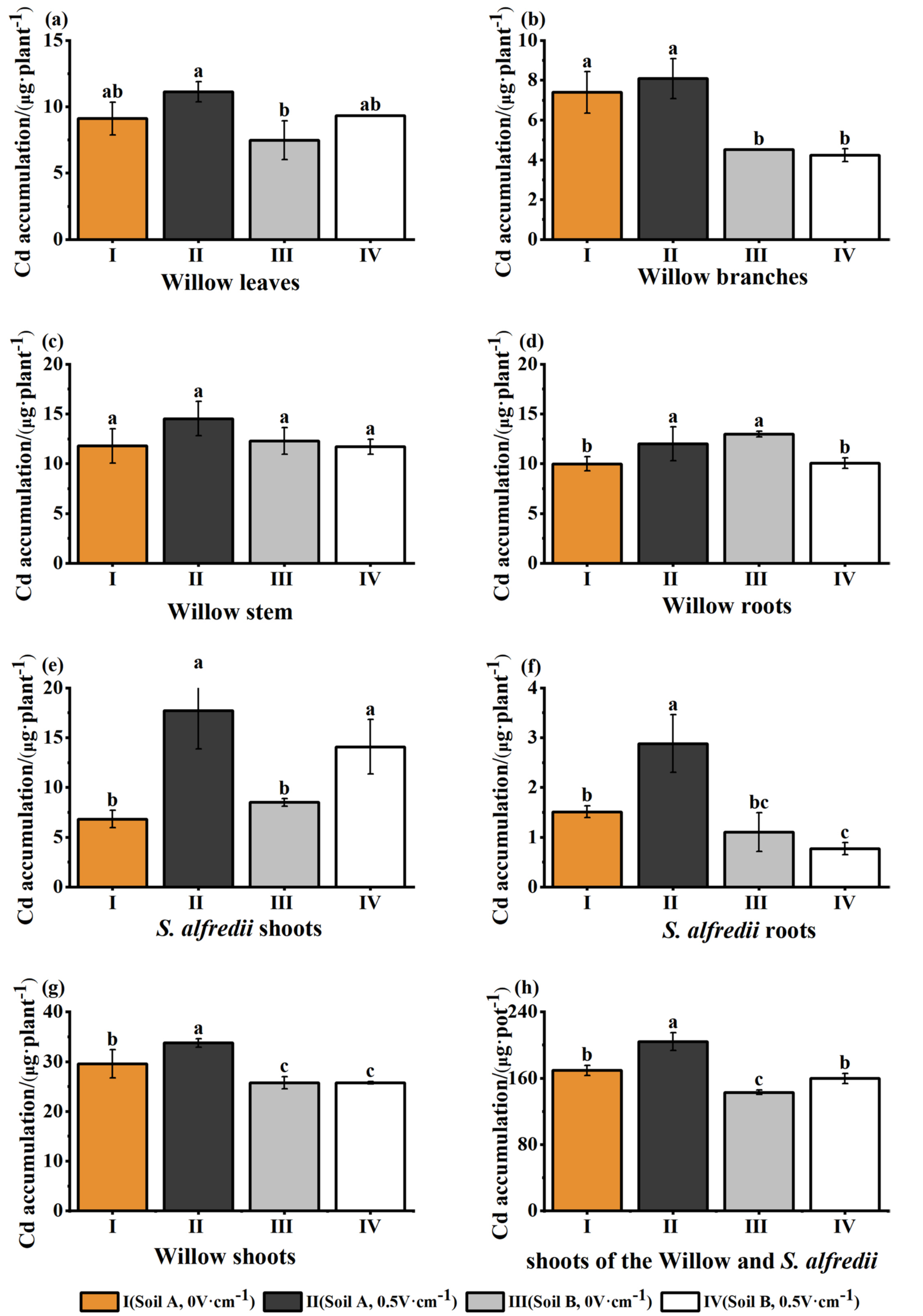

Figure 3. Effects of soil type on the accumulation of Cd in willow and *S. alfredii* under AC electric field.

efficiently and rapidly from the roots to the above-ground parts of the plant, leading to a further increase of growth in plant biomass. In this study, the growth of willow and *S. alfredii* exhibited variations in different soil types. Zheng et al. observed that the growth of certain *Sedum* species grew better at pH 5.4 or 6.4 compared to pH 8.2, suggesting that different soil pH levels can indeed affect plant growth[40]. Additionally, Ma et al. found that alkaline stress inhibits growth, increases electrolyte leakage, disrupts stomata integrity, and has inhibitory effects on plant growth and development[41]. In the present study, the growth of willow and *S. alfredii* in soil with high alkalinity (soil B) was inhibited, especially for willow. In acidic soils, the application of an AC electric field proved more effective in increasing the fresh weight of *S. alfredii* than in high pH soil B. Moreover, willow growth in dry matter weight was further reduced by the AC electric field treatment in the alkaline soil.

Proper energization not only promotes plant growth and metabolism but also facilitates the uptake and translocation of soil heavy metals by plants[42]. Xu et al. discovered that AC electric field significantly enhanced the growth and Cd accumulation in *Solanum nigrum*[43]. The AC electric field improves the effectiveness and mobility of Cd in the soil, leading to the desorption of Cd ions from soil particles and the increase of Cd concentration in the soil solution. Consequently, this promotes Cd uptake by plant roots[44]. Consistent with these findings, our study demonstrated that the AC electric field treatment resulted in increased Cd concentration in all parts of willow (except branches) and *S. alfredii* compared to the control treatment (without AC electric field treatment). Particularly, the aboveground parts of the plants exhibited higher Cd absorption. Previous studies have shown that there are variations in Cd accumulation among different parts of willow, with higher rates of Cd accumulation observed in soils with lower pH levels[45]. In this study, the combination of acidic soil and AC electric field treatments proved to be the most effective in promoting Cd accumulation in the shoot parts of willow and *S. alfredii*. On the other hand, the decrease in shoot Cd accumulation of these plants under alkaline soil and AC electric field treatment can be attributed to the hydrolysis or precipitation of toxic metal ions caused by the presence of OH^- ions as soil pH increases. This phenomenon hinders their migration and adversely affects their accumulation[46]. Moreover, the alkalinity of soil leads to the precipitation of Cd ions, reducing their mobility and effectiveness, thereby inhibiting Cd accumulation in the soil by willow and the shoots of *S. alfredii*. The inhibitory effect of alkaline conditions on the growth of willow and *S. alfredii* further influences the accumulation of heavy metals in different parts of these plants. Considering that phytoremediation primarily relies on Cd absorption from the soil and accumulation in plant shoots of willows and *S. alfredii*, it is crucial to enhance the biomass of these plants to increase their capacity for above-ground Cd uptake. *S. alfredii* -willow intercropping combines the highly accumulative characteristics of *S. alfredii* and the deep-rooted characteristics of willow, which is more conducive to remedy the heavy metal contaminated soil in long term. The AC remediation technique promoted phytoremediation efficiency in both acidic and alkaline soils although phytoremediation was more applicable in acidic soil. Its effectiveness in varying moisture content has been demonstrated, but further trials are needed for other soil types or physicochemical environments.

Conclusions

In this study, the combination of AC electric fields and *S. alfredii* -willow intercropping demonstrated effectiveness in remedying soil Cd contamination, with higher plant uptake observed in acidic soils compared to alkaline soils. Utilizing of AC electric fields with varying intensities, in combination with different cropping patterns or in soils with different properties, may be a universal approach to addressing heavy metal contamination. However, further optimization is required to enhance AC electric field-assisted phytoremediation in alkaline soils. This study is a simulation test, and there is room for improvement in field trials. We suggest improving planting methods and AC electric field arrangements for practical feasibility.

Data availability

The raw data supporting the conclusions of this article are available from the corresponding author upon reasonable request.

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Aiai Bu contributed to data curation, visualization, writing—original draft preparation. Guihua Yao contributed to investigation, validation. Chuikang Zhou: writing—original draft preparation. Zhansheng Mao, Jiawei Ma, Xianzhi Fang contributed to writing—reviewing and editing. Bo Liu contributed to investigation. Dan Liu contributed to supervision. Zhengqian Ye contributed to conceptualization, data curation, writing—reviewing and editing. All authors reviewed the manuscripts and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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