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# Effects of intercropping system on phytoremediation of cadmium contaminated farmland soil in the central Hanjiang River Basin

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**Introduction:** Cadmium (Cd) pollution poses a global environmental challenge, especially in the rapidly developing central Han River Basin. Cd contamination in farmland soil there is becoming increasingly serious, warranting studies on remediation using hyperaccumulators.

**Methods:** To explore the phytoremediation effects of different planting patterns on typical farmland soil (moisture soil) contaminated with Cd, two Cd hyperaccumulators (*Sedum alfredii* and *Solanum nigrum*) suitable for growth in Hubei Province and two common crops (celery and soybean) were selected for pot experiments involving monocropping and intercropping.

**Results:** The results showed that the absorption and accumulation of Cd by the two hyperaccumulators were as follows:  $Cd_{S. alfredii} > Cd_{S. nigrum}$ , and the Cd concentrations in plants were as follows:  $Cd_{shoot} > Cd_{root}$ , indicating a strong ability to transfer Cd from the root to the shoot. The Cd concentrations in each part of celery were as follows:  $Cd_{root} > Cd_{stem} > Cd_{leaf}$ , while in soybean as follows:  $Cd_{root} > Cd_{leaf} > Cd_{stem}$ . The Cd concentration in plants was significantly correlated with soil properties, negatively with pH ( $-0.68^{**}$ ) and positively with both total and available Cd in the soil ( $0.99^{**}$ ). The accumulation of Cd in plants in high-Cd soil treatments was significantly higher than that in low-Cd soil treatments ( $p < 0.05$ ). The accumulation of Cd in plants ranged from 0.04 to 1.02 mg, and the Cd removal rate from the soil was between 1.96 and 19.68%. Intercropping enhanced the overall remediation efficiency. In the *S. alfredii*-celery and *S. nigrum*-soybean systems, the biomass of crops increased, the Cd absorption by the hyperaccumulators was significantly increased ( $p < 0.05$ ).

**Discussion:** Both intercropping systems demonstrated relatively high soil Cd removal efficiency. Therefore, the two intercropping systems were suitable phytoremediation methods for Cd-polluted farmland soil in the central Han River Basin. Intercropping with the corresponding hyperaccumulators in fields of typical crops celery or soybean could reduce the food safety risk of these crops while simultaneously achieving phytoremediation.

## KEYWORDS

plant intercropping, cadmium, Hanjiang River Basin, phytoremediation, farmland soil



## Introduction

On a global scale, soil heavy metal pollution represents one of the most common and widespread environmental problems (Alberto Then et al., 2024). Heavy metals are acknowledged as significant pollutants in soil owing to their toxicity, long residual time, and capacity to accumulate in organisms through the food chain (Ahmed et al., 2021; Shi et al., 2024). Cadmium (Cd) is a heavy metal pollutant widely existing in agricultural soil and water with strong migration, which is easily absorbed by crop roots and accumulated in human body (Li et al., 2025). Cd primarily affects plants by interfering with the physiological metabolism of their roots, leading to stunted root growth and impaired uptake of water and nutrients, and this eventually leads to plant malnutrition (Wang et al., 2018). Furthermore, Cd reduces the activity of key plant enzymes and damages the cell membrane system, negatively impacting various physiological and biochemical processes. These effects collectively contribute to decreased crop yield and quality (Ali et al., 2018).

In a global context, high-quality freshwater and farmland soils are scarce natural resources in many watershed areas (Qi et al., 2024). The Hanjiang River, the largest branch of the Yangtze, spans an impressive distance of 1,577 kilometers, flowing through Shaanxi and Hubei Provinces before eventually converging with the Yangtze in Wuhan City, and this expansive river covers a vast area of 159,000 square kilometers (Li et al., 2023). Xiangyang is the central city of Hanjiang River Basin, has a total area of 19,700 square kilometers and a permanent population of 5,278,500. The Xiangyang section of Hanjiang River stretches approximately 270 kilometers, with abundant freshwater resources and fertile soil, and it is a developed industrial and agricultural area in Hubei Province. According to investigations, the average geochemical background concentration of Cd in the central Hanjiang River Basin stands at  $0.27 \text{ mg kg}^{-1}$ , which is 2.78

times higher than the national average geochemical background value of  $0.097 \text{ mg kg}^{-1}$  (Nong et al., 2024). Therefore, the risk of Cd pollution in farmland soil in the central Hanjiang River Basin is relatively high and requires constant attention. In the agricultural soils of northwest Hubei Province, Cd levels have been detected to vary between 0.018 and  $7.64 \text{ mg kg}^{-1}$  (Li et al., 2006). It is of great practical significance to carry out remediation research on Cd pollution of farmland soil in the northwestern Hubei Basin.

Traditional remediation techniques for Cd contaminated soil include physical, chemical and biological methods. Although effective, there have some problems such as high engineering requirements, the risk of secondary pollution, elevated costs, and potential harm to soil fertility (Soltanian et al., 2024). In contrast, phytoremediation offers a cost-effective, easy-to-implement, and environmentally friendly alternative. The natural presence of hyperaccumulator plants further provides excellent resources for this approach (Balint and Boaj, 2024). Phytoremediation typically involves cultivating hyperaccumulator plants to reduce or remove environmental pollutants. However, this method also has limitations, including the slow growth and limited economic value of most hyperaccumulator species (Kumar et al., 2013; Ariyachandra et al., 2023). Additionally, traditional phytoremediation often requires suspending crop production, which negatively impacts farmland productivity and is less likely to be accepted by local farmers (Lewandowski et al., 2006). Given the scarcity of land resources and the demands of a large population, developing intercropping-based remediation techniques that allow for simultaneous production and remediation is of great importance (Ning et al., 2023).

*Sedum alfredii* Hance is a perennial herb in the Crassulaceae family and the genus *Sedum*. It was first discovered in ancient lead-zinc mining areas in Southeast China (Lu et al., 2009). Due to its strong tolerance to excessive cadmium and lead in soil and its hyperaccumulation traits, it has been identified as a native Cd hyperaccumulator. Research has shown that the Cd concentration in the stem and leaf of *S. alfredii* can reach up to  $11,000 \text{ mg kg}^{-1}$  (Zhou and Qiu, 2005). *Solanum nigrum* L. is an annual herb in the family Solanaceae and the genus *Solanum*, it is widely distributed in temperate to tropical regions of Europe, Asia and America, and is almost found throughout China. With its large biomass and a certain tolerance to Cd in soil, *S. nigrum* recognized as a typical Cd-hyperaccumulator (Wang J. et al., 2024; Wang Z. et al., 2024; Yang et al., 2024).

The moisture soil is prevalent in Hubei Province, covering an area of  $5.86 \times 10^5$  hectares, which accounts for 11.06% of the province's total arable land ( $5.30 \times 10^6$  hectares). This type of soil is formed from river sediments through long-term cultivation and maturation. It exhibits relatively high fertility and is one of the important agricultural soil types in Hubei Province. Moreover, the Hanjiang River Basin is characterized by notable ecological fragility and heightened susceptibility to Cd contamination. Consequently, there is an urgent need to explore Cd phytoremediation strategies for moisture soil in the central region of the Hanjiang River Basin.

In this study, two Cd hyperaccumulators (*S. alfredii* and *S. nigrum*) adapted to grow in Hubei Province, along with two common crops (celery and soybean), were selected. Pot experiments for Cd-contaminated soil remediation were conducted under monocropping and intercropping systems. The aim was to explore the remediation effects of different planting patterns on typical farmland moisture soil in the central Han

River Basin, and to provide valuable insights for reducing the food safety risk of crops while conducting phytoremediation.

## Materials and methods

### Experimental plants and soils

Celery (*Apium graveolens* Linn) and soybeans (*Glycine max* (L.) Merr.), which were conventionally grown locally, were selected as the experimental crops, the celery variety was JR-1, and the Soybean variety was ZH-13. Two Cd hyperaccumulators (*S. alfredii* and *S. nigrum*) were selected according to the climatic characteristics of the Han River Basin and combined with the growth characteristics of the experimental crops. The seedlings of celery, soybean, *S. alfredii* and *S. nigrum* were purchased from Xiangyang Academy of Agricultural Sciences. Seedlings of these varieties were cultivated in accordance with the breeding matrix (patent license CN 101057542A). The seeds were surfacing with 3% hydrogen peroxide for 15 min, then thoroughly rinsed with ultra-pure water, and placed in a wet matrix indoors (25 °C, 75% RH), healthy and growth-stable seedlings were selected and transplanted into the pots.

The moisture soil was collected from farmland (32°11'47.321" N; 112°23'48.538" E) in Shuanggou Town, Xiangzhou District, Xiangyang City, Hubei Province (Figure 1). This region is a typical northern subtropical monsoon area in the central part of Hanjiang River Basin, the annual average temperature is 16.9 °C, the annual sunshine duration is approximately 1,780 h, and the annual average precipitation is 1098.4 mm. Industrial pollution is the main cause of Cd pollution in the farmland soil of this area. Randomly collected surface soil (0–20 cm) was mixed using wooden spades and stored in

cotton cloth bags. The soil samples were air dried at room temperature and sieved through a 10-mesh nylon sieve.

### Pot experiment design

The moisture soil was prepared with different Cd concentrations to simulate different levels of Cd stress. The low Cd soil was the collected moisture soil, with a total Cd concentration of 0.52 mg kg<sup>-1</sup> (Table 1), which is slightly higher than the risk screening value (pH ≤ 7.5, C<sub>Cd</sub> = 0.30 mg kg<sup>-1</sup>; pH > 7.5, C<sub>Cd</sub> = 0.60 mg kg<sup>-1</sup>) for soil environmental pollution quality in agricultural land (Table 2) specified in the Chinese National Standard (GB15618-2018) (Luo et al., 2020). The high Cd soil was prepared to exceed the risk control standard by adding exogenous Cd in the form of CdCl<sub>2</sub>·2.5H<sub>2</sub>O, resulting in a total Cd concentration of 3.08 mg kg<sup>-1</sup>. The physicochemical properties of the soils used are shown in Table 1.

Pot experiments were conducted in a glasshouse at the School of Food Science and Chemical Engineering, Hubei University of Arts and Science, Xiangyang (112°2'28.669" E, 32°0'5.602" N) for 100 days. Three types of treatments were established: blank control (Control), monocropping, and intercropping, which were planted in the original and Cd-amended soils, respectively (Table 3). There was a total of 18 groups of processing, and each with three replicates. Plastic pots (27.5 cm high × 26.0 cm diameter) were used, and each filled with 8.0 kg of soil. After filling the pots with soil, the moisture content was maintained at approximately 70% of the field water holding capacity using the weight method for 7 days to allow the Cd stabilization. A solid compound fertilizer (the ratio of nitrogen, phosphorus and potassium was 15:15:15) was applied to the soil in an amount of 7.00 g per pot. For both monocropping and intercropping treatments, five seedlings were planted per pot. Weeding was performed every

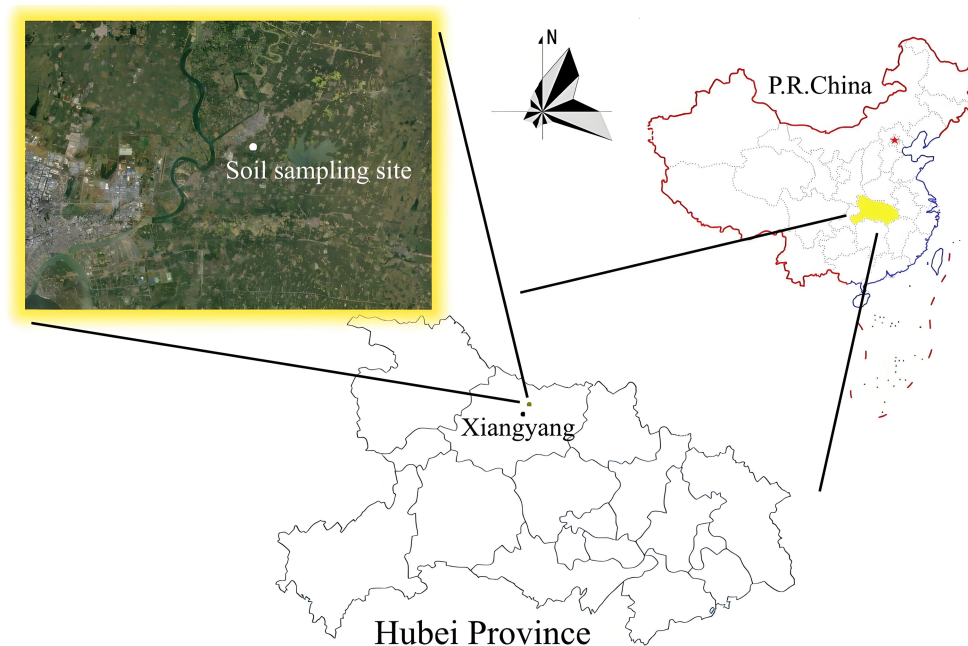


FIGURE 1  
Locations of soil sampling in Shuanggou Town, Xiangzhou District, Xiangyang City, Hubei Province.

TABLE 1 Soil physicochemical properties in pot experiment.

| Soil type     | Geologic origin    | Sample  | pH          | Organic matter g kg <sup>-1</sup> | Cation exchange capacity cmol kg <sup>-1</sup> | specific surface area m <sup>2</sup> g <sup>-1</sup> | Clay content % | Available N g kg <sup>-1</sup> | Available P g kg <sup>-1</sup> | Available K g kg <sup>-1</sup> | Total Cd mg kg <sup>-1</sup> | Available Cd mg kg <sup>-1</sup> |
|---------------|--------------------|---------|-------------|-----------------------------------|------------------------------------------------|------------------------------------------------------|----------------|--------------------------------|--------------------------------|--------------------------------|------------------------------|----------------------------------|
| Moisture soil | Carbonate alluvium | Low Cd  | 6.24 ± 0.10 | 36.58 ± 2.73                      | 19.37 ± 1.22                                   | 147 ± 5.65                                           | 24.79 ± 1.41   | 0.23 ± 0.03                    | 0.11 ± 0.02                    | 0.15 ± 0.05                    | 0.52 ± 0.08                  | 0.13 ± 0.02                      |
|               |                    | High Cd | 6.17 ± 0.08 | 37.41 ± 3.09                      | 16.51 ± 0.85                                   | 152 ± 7.03                                           | 22.35 ± 1.16   | 0.21 ± 0.04                    | 0.092 ± 0.01                   | 0.13 ± 0.03                    | 3.08 ± 0.55                  | 0.61 ± 0.05                      |

Each value is the mean of three replicates ± standard derivation (SD).

4 weeks, and irrigation used the weighing method to maintain the soil moisture content at 70% of the field water holding capacity. Purified water was supplied every 1–2 days until harvest.

## Sample collection

After harvesting the intact plants, they were thoroughly rinsed with ultra-pure water to remove surface contaminants, then separated into roots, stems, and leaves carefully. The plant tissues were first heated in an oven at 105 °C for 30 min to deactivate enzymes, followed by drying at 65 °C until a constant weight was achieved. The dry weight of each plant part was recorded. Subsequently, the dried samples were pulverized and passed through a 100-mesh nylon sieve, and stored in polyethylene bags for further analysis.

Corresponding soil samples were collected alongside the plant samples. Soil samples were taken from top to bottom layers, mixed thoroughly, and placed in a cool and well-ventilated area to air dry. The soil samples were grinded, retaining plant residues and crushed gravels. All samples were first filtered through a 20-mesh nylon screen. After homogenization, a portion of them were removed for further grinding and were passed through a 100-mesh nylon screen, stored in polyethylene bags for future use.

## Sample analysis

### Plant sample

Accurately weighed 0.20 g plant samples in microwave digestion tank, 5.00 mL of HNO<sub>3</sub> (guarantee reagent) were added, then 1.00 mL of H<sub>2</sub>O<sub>2</sub> (guarantee reagent) were added after 2 h and let stand for 8 h in the high-pressure microwave digestion system (CEM Mars 6) at 180 °C for 45 min (Mamun et al., 2017). After concentrating the acid to 1.00 mL, the solution was diluted to a constant volume of 20 mL using 3% dilute HNO<sub>3</sub> (guarantee reagent). Finally, the Cd concentrations in the solutions were determined using an ICP-MS (Thermo Fisher Scientific X2) (Dong et al., 2022).

### Soil physicochemical properties

The soil pH was determined using a potentiometric method. The organic matter content in the soil was measured using the volumetric potassium dichromate method. The cation exchange capacity of the soil was determined by the extraction spectrophotometry of cobalt hexammine trichloride (HJ 889-2017) (Hadi et al., 2016). The clay content in the soil was analyzed utilizing a laser particle size analyzer (Malvern Panalytical Mastersizer 3000). Available nitrogen (N), phosphorus (P) and potassium (K) were measured according to the Kjeldahl method (GB 7173-1987) (Madagoudra et al., 2021), combined extraction and colorimetry (NY/T 1848-2010) (Militaru et al., 2019) and Combined extraction and colorimetry (NY/T 1849-2010) (Zhai et al., 2013), respectively.

### Soil total cadmium and available cadmium

Accurately weighed 0.10 g soil samples and sieved through a 100-mesh sieve before being placed into the polytetrafluoroethylene inner tanks of the digestion kettle. 3.00 mL nitric acid (HNO<sub>3</sub>, guarantee reagent) and 3.00 mL hydrofluoric acid (HF, guarantee reagent) were added and the mixture was allowed to sit for 8 h.

TABLE 2 The risk screening value and control value of soil Cd pollution in agricultural land (mg kg<sup>-1</sup>).

| Risk values of soil Cd pollution | pH ≤ 5.5 | 5.5 < pH ≤ 6.5 | 6.5 < pH ≤ 7.5 | pH > 7.5 |
|----------------------------------|----------|----------------|----------------|----------|
| Risk screening value             | 0.30     | 0.30           | 0.30           | 0.60     |
| Risk control value               | 1.50     | 2.00           | 3.00           | 4.00     |

TABLE 3 Pot experiment treatments and Cd concentrations.

| Soils         | Hyperaccumulators  | Cropping patterns          | Concentration levels | Treatments | Cd concentration in soil mg kg <sup>-1</sup> |
|---------------|--------------------|----------------------------|----------------------|------------|----------------------------------------------|
| Moisture soil | <i>S. alfredii</i> | Monoculture                | Low                  | SA-M-L     | 0.51 ± 0.025                                 |
|               |                    |                            | High                 | SA-M-H     | 3.09 ± 0.093                                 |
|               |                    | Intercropping with celery  | Low                  | SA-C-L     | 0.53 ± 0.031                                 |
|               |                    |                            | High                 | SA-C-H     | 3.10 ± 0.11                                  |
|               |                    | Intercropping with soybean | Low                  | SA-S-L     | 0.50 ± 0.021                                 |
|               |                    |                            | High                 | SA-S-H     | 3.09 ± 0.082                                 |
|               | <i>S. nigrum</i>   | Monoculture                | Low                  | SN-M-L     | 0.53 ± 0.019                                 |
|               |                    |                            | High                 | SN-M-H     | 3.08 ± 0.11                                  |
|               |                    | Intercropping with celery  | Low                  | SN-C-L     | 0.52 ± 0.022                                 |
|               |                    |                            | High                 | SN-C-H     | 3.07 ± 0.10                                  |
|               |                    | Intercropping with soybean | Low                  | SN-S-L     | 0.52 ± 0.018                                 |
|               |                    |                            | High                 | SN-S-H     | 3.10 ± 0.07                                  |
|               |                    | Celery monoculture         | Low                  | C-M-L      | 0.51 ± 0.013                                 |
|               |                    |                            | High                 | C-M-H      | 3.08 ± 0.04                                  |
|               |                    | Soybean monoculture        | Low                  | S-M-L      | 0.52 ± 0.011                                 |
|               |                    |                            | High                 | S-M-H      | 3.09 ± 0.06                                  |

Subsequently, 2.00 mL of perchloric acid (HClO<sub>4</sub>, guarantee reagent) were added and the entire mixture was transferred to the metal outer tank of the digestion kettle. The kettle was then placed in the oven and heated to 180 °C for 12 h to complete the digestion process. After the digestion was complete, the inner polytetrafluoroethylene tanks were placed on an electric hot plate and heated until the acid was drained to dryness, ensuring that no HF residue remained (Qi et al., 2024). Once dry, 1.00 mL of HNO<sub>3</sub> (guarantee reagent) was added to dissolve any remaining solids. The volume was then diluted to 50 mL using 3% dilute nitric acid (guarantee reagent), and the Cd concentrations in the solutions were determined by ICP-MS (Thermo Fisher Scientific X2) (Zheng et al., 2021; Yuan et al., 2022).

Accurately weighed 2.00 g soil samples with a 20-mesh sieve into a 50 mL centrifuge tube, mixed with 0.01 mol L<sup>-1</sup> CaCl<sub>2</sub> solution (guarantee reagent) and shocked for 2 h to ensure thorough mixing, centrifuged at 3,500 rpm for 5 min and filtered, then the Cd concentrations in the filtrate were used ICP-MS (Thermo Fisher Scientific X2) to determine (Guo et al., 2022; Qi et al., 2024).

transfer in the soil-plant system was comprehensively analyzed. The bio-concentration factor (BCF) and translocation factor (TC) were used as indicators of Cd's enrichment and transfer capacity (Tudi et al., 2020). The formulas for the BCF, TF, accumulation of Cd by plants (AC) and the removal rate of Cd in soil (RC) were as follows:

$$BCF = \frac{C_{shoot}}{C_{soil}} \quad (1)$$

$$TF = \frac{C_{shoot}}{C_{root}} \quad (2)$$

$$AC = \frac{C_{plant}}{M_{plant}} \quad (3)$$

$$RC = \frac{C_{soil-b} - C_{soil-a}}{C_{soil-b}} \times 100\% \quad (4)$$

## Heavy metal evaluation criteria

To assess the overall soil Cd rating, the soil environmental quality standard was used to control soil pollution risks from farmland (Table 2). The risk of pollution is high, necessitating strict control measures in principle (Zheng et al., 2021; Wang J. et al., 2024; Wang Z. et al., 2024). The capacity for Cd enrichment and

In Equation 1, C<sub>shoot</sub> represented the Cd concentration in the above-ground tissues of the plant, and C<sub>soil</sub> represented the Cd concentration in the soil. In Equation 2, C<sub>shoot</sub> represented the Cd concentration in the above-ground tissues of the plant, and C<sub>root</sub> represented the Cd concentration in the root of the plant. In Equation 3, C<sub>plant</sub> represented the Cd concentration of the entire plant, and M<sub>plant</sub> represented the dry weight of the entire plant. In Equation 4,

$C_{\text{soil-b}}$  represented the soil Cd concentration before planting, and  $C_{\text{soil-a}}$  represented the soil Cd concentration after planting.

## Statistical analyses

Statistical analyses were performed using one-way analysis of variance (ANOVA) for continuous variables and Pearson's chi-squared test for categorical data to assess inter-group differences. Blind controls and the national standard reference material GSV-2 were included in every batch of samples to ensure quality control. The correlation analysis was conducted using IBM SPSS Statistics Version 22.0 for Windows (IBM, Armonk). Statistical significance levels are denoted as \* ( $p < 0.05$ ) and \*\* ( $p < 0.01$ ). Descriptive statistical analysis and data visualization were performed using Origin pro 2022 (OriginLab Corp., Northampton) and Excel 2019 (Microsoft Corp., Waltham). Each value represents the mean of four repetitions  $\pm$  standard deviation (SD).

## Results

### The influence of different planting patterns on plant biomass

The biomass of the hyperaccumulators *S. alfredii* and *S. nigrum* in different planting patterns of monocropping and intercropping in low-Cd and high-Cd soils was shown in Figure 2. In the SA-M-L treatment, the shoot and root biomass (dry weight) of *S. alfredii* was the highest, which were  $1.43 \pm 0.11$  g and  $0.19 \pm 0.03$  g, respectively. In the SA-S-H treatment, the shoot and root biomass of *S. alfredii* was the lowest, which were  $1.06 \pm 0.05$  g and  $0.08 \pm 0.02$  g, respectively. Compared with the monocropping of *S. alfredii*, the celery and soybean had significant effects on the shoot biomass of *S. alfredii* ( $p < 0.05$ ), while they had an inhibitory effect on the root biomass and decreased by 15.79 and 26.32%, respectively. The plant biomass in the high-Cd soil treatment was significantly lower than that in the low-Cd soil ( $p < 0.05$ ).

The biomass of shoot and root of *S. nigrum* in the SN-S-L treatment was the highest, which was  $2.71 \pm 0.22$  g and  $0.33 \pm 0.05$  g respectively, while the biomass of shoot and root of SN-M-H and SN-C-H was the lowest, which was  $1.93 \pm 0.17$  g and  $0.18 \pm 0.04$  g, respectively. Compared with the monocropping of *S. nigrum*, intercropping with celery and soybeans significantly increased the aboveground biomass of *S. nigrum* ( $p < 0.05$ ), increasing by 12.78 and 19.38%, respectively. The root biomass of solana decreased by 34.48% when intercropped with celery and increased by 13.79% when intercropped with soybeans. The plant biomass in the high-Cd soil treatment was also significantly lower than that in the low-Cd soil ( $p < 0.05$ ).

The biomass of celery and soybean in different planting patterns was shown in Figure 3. In the SA-C-L treatment, the root, stem and leaf biomass of celery was the highest, which were  $0.93 \pm 0.04$  g,  $7.67 \pm 0.15$  g and  $4.75 \pm 0.09$  g, respectively. Compared with the monocropping of celery, intercropping of hyperaccumulators significantly increased the biomass of celery ( $p < 0.05$ ). Especially, intercropping with *S. alfredii* has the highest effect on the increase of celery biomass. In low-Cd and high-Cd soils, the biomass of root, stem and leaf increased by 78.85, 105.63, 107.42 and 51.02%, 122.74, 107.77%, respectively.

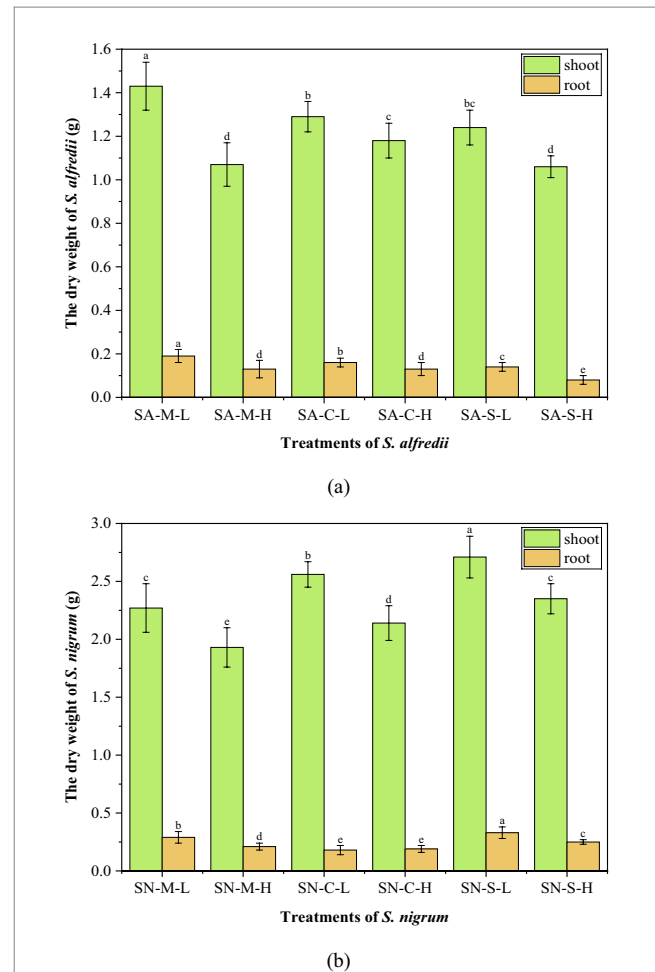


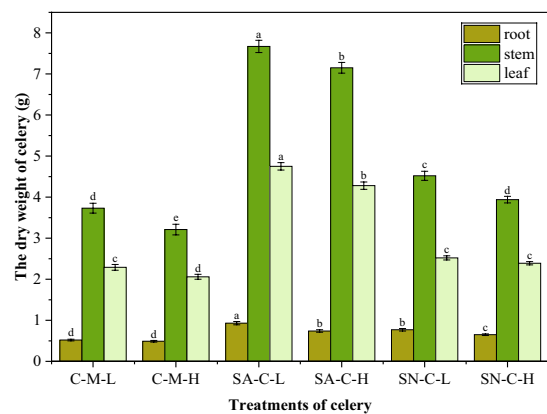
FIGURE 2

Biomass (dry weight) of *S. alfredii* (a) and *S. nigrum* (b) under different planting patterns. Each value is the mean of three replicates  $\pm$  standard deviation (SD). Different letters in columns denote significant difference at  $p < 0.05$  level between treatments. Shoot indicates the above-ground part of a plant, root indicates the underground part of a plant. SA indicates *S. alfredii*, SN indicates *S. nigrum*, M indicates monocropping, C indicates intercropping with celery, S indicates intercropping with soybean, L indicates low Cd concentration level, and H indicates high Cd concentration level.

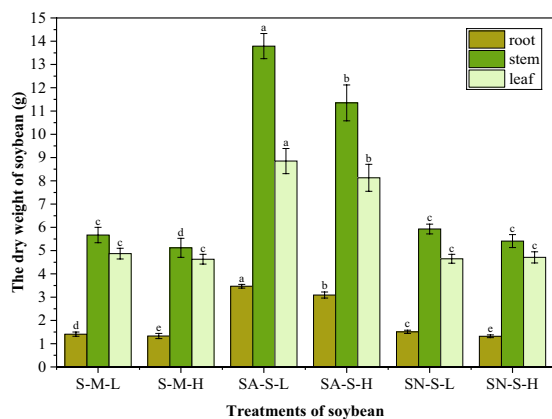
In the SA-S-L treatment, the root, stem and leaf biomass of soybean was the highest, which were  $3.47 \pm 0.08$  g,  $13.79 \pm 0.94$  g and  $8.85 \pm 0.54$  g, respectively. Compared with the monocropping, intercropping with *S. alfredii* significantly increased the biomass of root, stem and leaf ( $p < 0.05$ ). In low-Cd and high-Cd soils, the root, stem and leaf biomass of soybean increased by 146.10, 143.21, 81.72 and 132.33%, 121.68, 75.59%, respectively. In the intercropping treatment with *S. nigrum*, there was no significant difference in the biomass of soybean root, stem and leaf ( $p < 0.05$ ).

### The influence of different planting patterns on the Cd concentration in the shoot and root

In different planting patterns, the Cd concentration in *S. alfredii* and *S. nigrum* was all shown as  $Cd_{\text{shoot}} > Cd_{\text{root}}$ , which indicated that the hyperaccumulators had a strong ability to transfer Cd to the



(a)



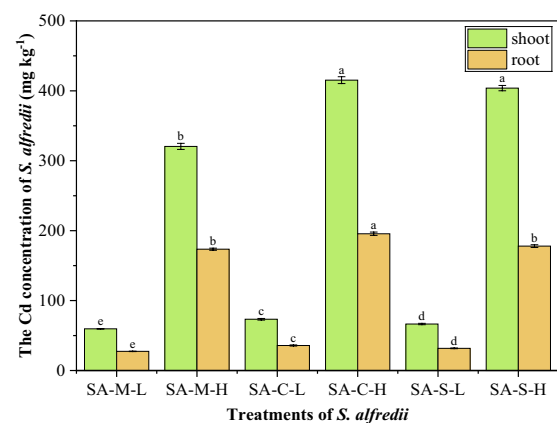
(b)

FIGURE 3

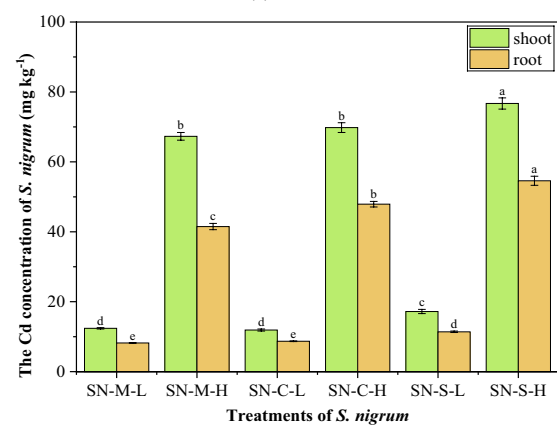
Biomass (dry weight) of celery and soybean under different planting patterns. Each value is the mean of three replicates  $\pm$  standard derivation (SD). Different letters in columns denote significant difference at  $p < 0.05$  level between treatments. Root indicates the underground part of a plant, stem indicates the stem part of a plant, leaf indicates the leaf part of a plant. M indicates monocropping, C indicates intercropping with celery, S indicates intercropping with soybean, L indicates low Cd concentration level, and H indicates high Cd concentration level.

above-ground part. In each treatment, the Cd concentrations in the shoot and the root of the *S. alfredii* were 59.60–415.30  $\text{mg kg}^{-1}$  and 27.40–195.60  $\text{mg kg}^{-1}$  respectively, while the Cd concentrations in the shoot and the root of the *S. nigrum* were 11.90–76.70  $\text{mg kg}^{-1}$  and 8.20–54.60  $\text{mg kg}^{-1}$ , respectively (Figure 4). It was found that *S. alfredii* was more effective than *S. nigrum* in remediation the Cd-contaminated farmland soil in this area. In the intercropping treatments of *Sedum australis*-celery and *Solanum nigrum*-soybean, the hyperaccumulation plants had a significant promoting effect on the absorption of cadmium in the soil ( $p < 0.05$ ). The shoot and root of SA-C-L and SA-C-H were  $73.30 \pm 1.15 \text{ mg kg}^{-1}$ ,  $35.80 \pm 0.77 \text{ mg kg}^{-1}$  and  $415.30 \pm 4.90 \text{ mg kg}^{-1}$ ,  $195.60 \pm 2.36 \text{ mg kg}^{-1}$ , respectively. The shoot and root of SN-S-L and SN-S-H were  $17.20 \pm 0.61 \text{ mg kg}^{-1}$ ,  $11.40 \pm 0.27 \text{ mg kg}^{-1}$  and  $76.70 \pm 1.62 \text{ mg kg}^{-1}$ ,  $54.60 \pm 1.33 \text{ mg kg}^{-1}$ , respectively.

The Cd concentration of celery and soybean in different planting patterns were shown in Figure 5. In each treatment of celery cultivation, the Cd concentration was shown as:



(a)



(b)

FIGURE 4

The Cd concentration (dry weight) of *S. alfredii* (a) and *S. nigrum* (b) under different planting patterns. Each value is the mean of three replicates  $\pm$  standard derivation (SD). Different letters in columns denote significant difference at  $p < 0.05$  level between treatments. Shoot indicates the above-ground part of a plant, root indicates the underground part of a plant.

$\text{Cd}_{\text{root}} > \text{Cd}_{\text{stem}} > \text{Cd}_{\text{leaf}}$ . The Cd concentration in the root, stem and leaf of C-M-H was the highest, which were  $15.60 \pm 0.76 \text{ mg kg}^{-1}$ ,  $11.30 \pm 0.51 \text{ mg kg}^{-1}$  and  $9.35 \pm 0.77 \text{ mg kg}^{-1}$ , respectively. Compared with celery monocropping, the Cd concentration in the root, stem and leaf of celery intercropped with *S. alfredii* was decreased significantly ( $p < 0.05$ ). Especially, the Cd concentration in the root, stem and leaf of SA-C-H decreased by 39.74, 41.24 and 43.10%, respectively, compared with C-M-H. The Cd concentration in the root, stem and leaf of celery intercropped with *S. nigrum* was not decreased significantly, and the Cd concentration in the root, stem and leaf of SN-C-L increased by 5.76, 19.63 and 11.86%, respectively, compared with C-M-L. The Cd concentration in soybean was as follows:  $\text{Cd}_{\text{root}} > \text{Cd}_{\text{leaf}} > \text{Cd}_{\text{stem}}$ . The highest Cd accumulation was observed in the SA-S-H treatment, with concentrations of  $26.40 \pm 0.95 \text{ mg kg}^{-1}$  in root,  $11.90 \pm 0.12 \text{ mg kg}^{-1}$  in stem, and  $15.6 \pm 0.30 \text{ mg kg}^{-1}$  in leaf, respectively. Compared to soybean monoculture, intercropping with *S. alfredii* significantly enhanced Cd accumulation in all soybean tissues ( $p < 0.05$ ). In contrast, intercropping with *S. nigrum* was not result in significant

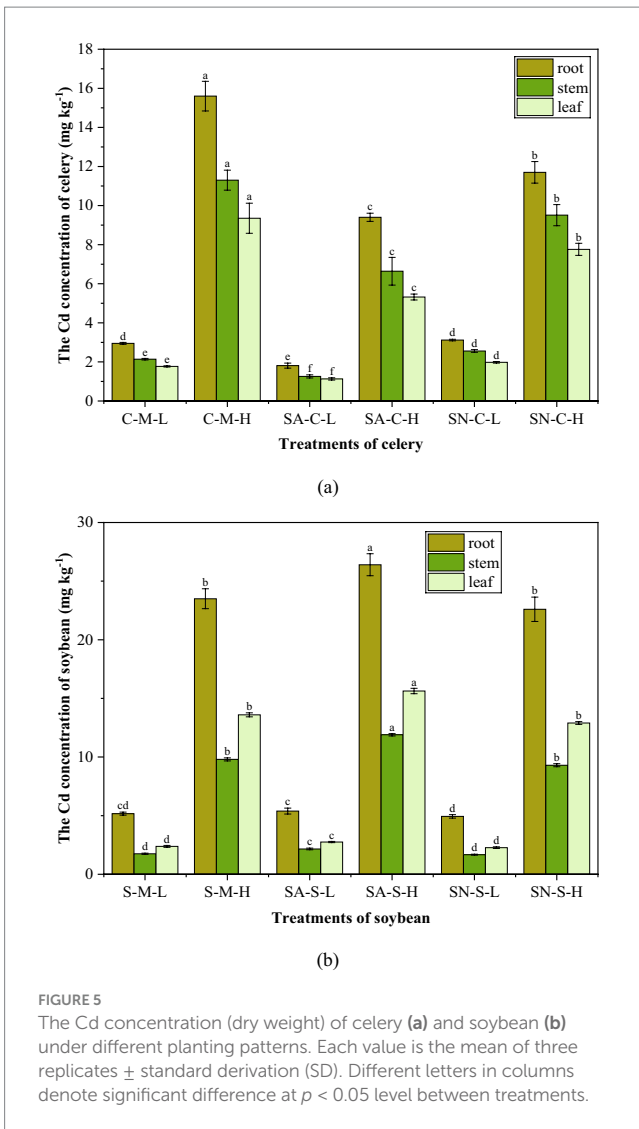


FIGURE 5

The Cd concentration (dry weight) of celery (a) and soybean (b) under different planting patterns. Each value is the mean of three replicates  $\pm$  standard deviation (SD). Different letters in columns denote significant difference at  $p < 0.05$  level between treatments.

difference in Cd concentration across root, stem, or leaf tissues. Additionally, no significant variations in Cd accumulation were observed between low-Cd and high-Cd soil treatments.

## The correlation between plant and soil properties in different planting patterns

In different planting patterns, the soil pH, total Cd concentration and available Cd concentration were shown in Figure 6. Compared with control, the soil pH in the SA-M-H, SA-C-L and SA-C-H treatments decreased significantly ( $p < 0.05$ ), reducing by 7.78, 11.70 and 13.13%, respectively. There was no significant difference in soil pH among the other treatments. It indicated that intercropping *S. alfredii* with celery was significantly reduced the soil pH ( $p < 0.05$ ).

Compared with control, the total Cd concentration in the soil decreased. In the low-Cd soil treatments, the Cd concentration in the SA-M-L and SA-C-L treatments decreased by 28.85 and 19.23%, respectively. In the high-Cd soil treatments, the Cd concentration in the SA-M-H, SA-C-H and SN-S-H

decreased by 24.03, 18.51 and 12.66%, respectively. The *S. alfredii* had the highest reduction amplitude in the monocultural treatments. Compared with control, the concentration of available Cd in the soil in different planting patterns all decreased. The concentration of available Cd in low-Cd soil treatments decreased significantly ( $p < 0.05$ ), among which the Cd concentration in SA-M-L, SA-C-L and SN-S-L decreased by 23.08, 38.46 and 30.77%, respectively. In the high-Cd soil treatments, except for the reduction of SN-S-H by 11.48%, the differences in the available Cd concentration in the other treatments were not significant.

Correlation analyses of plant biomass, plant Cd concentration, soil pH, total Cd and available Cd in soil were conducted (Table 4). The results revealed that plant Cd concentration exhibited an extremely significant negative correlation with soil pH ( $r = -0.68$ ,  $p < 0.01$ ), while soil total Cd and soil available Cd showed an extremely significant positive correlation ( $r = 0.99$ ,  $p < 0.01$ ). Plant biomass displayed a negative but non-significant association with both soil pH and soil Cd concentration ( $p > 0.05$ ). Similarly, plant Cd concentration showed a positive but non-significant relationship with soil Cd concentration ( $p > 0.05$ ).

## The bioconcentration factor, translocation factor, Cd accumulation of plants and the Cd removal rate of soil

The BCF and TF of each plant in different planting patterns were shown in Figures 7a,b. Compared with the monoculture model, the BCF of *S. alfredii* in the intercropping mode increased significantly ( $p < 0.05$ ), among which SA-C-L and SA-C-H treatments were  $138.30 \pm 6.79$  and  $133.97 \pm 5.96$  respectively, increased by 18.35 and 29.17% respectively; In the low-Cd soil treatment, *S. alfredii* TF decreased by 5.96 and 3.67% respectively, and in the high-Cd soil treatment, it increased by 14.59 and 22.70%, respectively. Compared with the monoculture model, the BCF of *S. nigrum* in the intercropping mode increased by 41.37 and 13.23%, respectively, in SN-S-L and SN-S-H treatments, while the differences in the other treatments were not significant ( $p > 0.05$ ). In the low-Cd soil treatment, the TF of solanum nigra decreased by 9.27 and 0.66% respectively, and in the high-Cd soil treatment, it decreased by 9.88 and 13.58%, respectively.

Compared with the monoculture model, the BCF of celery in the SA-C-L and SA-C-H treatments decreased by 41.20 and 42.39% respectively, while the BCF in the SN-C-L treatment increased by 13.82%. The TF of celery in the SN-C-L and SN-C-H treatments increased by 9.77 and 12.12% respectively, while there was no significant difference in TF between celery intercropping with *S. alfredii*. Compared with the monoculture model, the BCF of soybean in the SA-S-L and SA-S-H treatments increased by 23.68 and 17.70% respectively, while there was no significant difference in BCF between soybean intercropped with *S. nigrum*. The TF in the SA-S-L treatment increased by 13.75%, while there was no significant difference in TF of the other treatments.

The accumulation of Cd in each plant and the removal rate of Cd in the soil in different planting patterns were shown in Figures 7c,d.

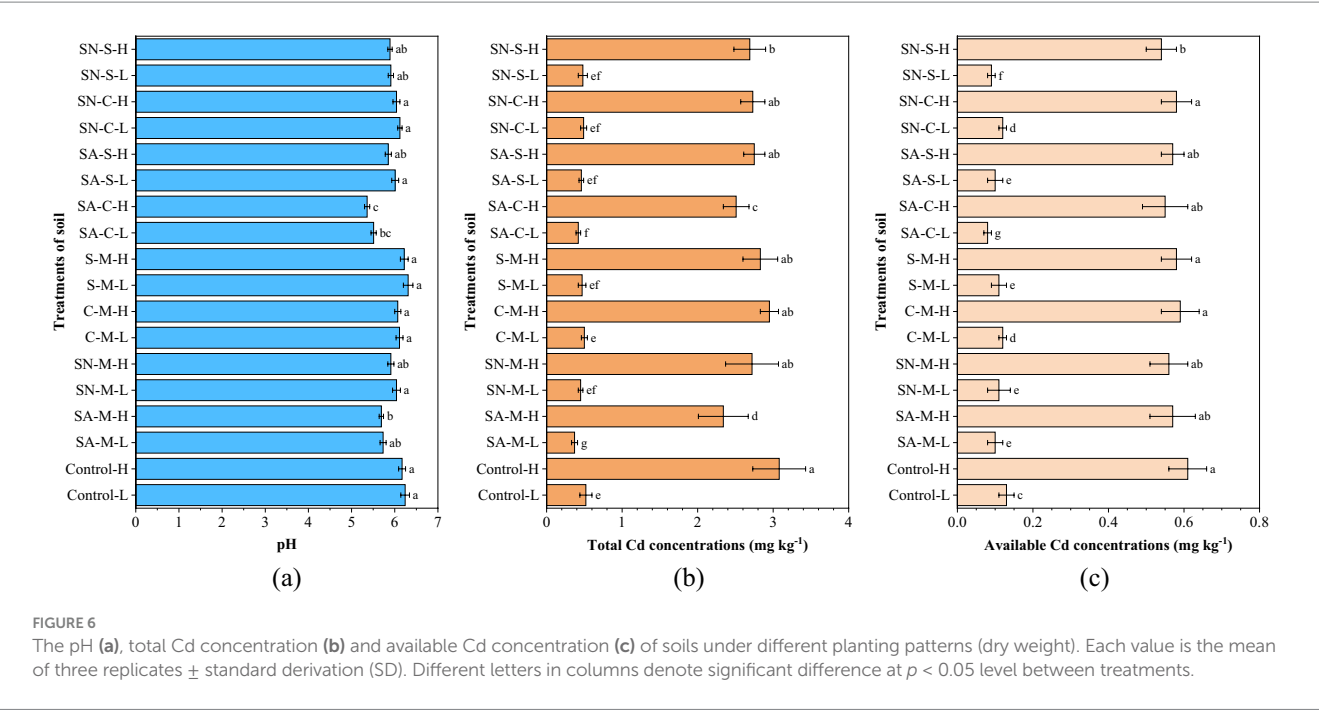


TABLE 4 Correlation analysis of plant biomass, plant Cd, soil pH, total Cd and available Cd.

| Correlation analysis of Plant and Soil | Plant biomass | Plant Cd | Soil pH | Soil total Cd | Soil available Cd |
|----------------------------------------|---------------|----------|---------|---------------|-------------------|
| Plant biomass                          | 1             |          |         |               |                   |
| Plant Cd                               | 0.33          | 1        |         |               |                   |
| Soil pH                                | -0.18         | -0.68**  | 1       |               |                   |
| Soil total Cd                          | -0.08         | 0.42     | -0.09   | 1             |                   |
| Soil available Cd                      | -0.11         | 0.48*    | -0.12   | 0.99**        | 1                 |

\*in columns denote significant difference at  $p < 0.05$  level;  
\*\*in columns denote significant difference at  $p < 0.01$  level.

The accumulation of Cd in plants was within the range of 0.04 to 1.02 mg. In the SA-S-H treatment, the accumulation of Cd in soybean was the highest at  $1.02 \pm 0.05$  mg. The accumulation of Cd in celery in the C-M-L treatment was the lowest, which was  $0.04 \pm 0.01$  mg. The Cd accumulation of the four plants was as follows: *S. alfredii* > Soybean > *S. nigrum* > celery. The Cd accumulation in the High-Cd soil treatment was significantly higher than that in the low-Cd soil treatment ( $p < 0.05$ ).

The removal rate of Cd in the soil ranged from 1.96 to 19.68%. The highest removal rate of Cd in the soil in the SA-C-H treatment was  $19.68 \pm 1.13\%$ . The removal rate of Cd in the soil was the lowest in the C-M-L treatment, which was  $1.96 \pm 0.04\%$ . The removal rate of Cd in the soil of each treatment was as follows: *S. alfredii*-celery intercropping > *S. alfredii* monocropping > Soybean monocropping > *S. nigrum*-soybean intercropping > *S. nigrum* monocropping > *S. alfredii*-soybean intercropping > *S. nigrum*-celery intercropping > celery monocropping. The Cd removal rate of high-Cd soil treatment was significantly higher than that of low-Cd soil treatment ( $p < 0.05$ ).

Discussion

Effects of planting patterns on plant growth and Cd accumulation

The stress effect of soil Cd caused serious harm to the growth and development of crops (Ali et al., 2023; Boorboori and Zhang, 2024). In Cd-contaminated soil, the adoption of the hyperaccumulator-crop intercropping model could promote crop growth and reduce the Cd concentration in crops. Compared with the monoculture mode, the *S. alfredii* intercropping increased the shoot biomass of corn and ryegrass, while reducing the Cd concentration in these two plants (Hu et al., 2014). The intercropping of rape and *S. alfredii* reduced the accumulation of Cd in the rapeseed (Cao et al., 2024). In this study, intercropping with hyperaccumulator significantly increased the biomass of celery ( $p < 0.05$ ) while simultaneously decreasing Cd accumulation in the crop. In contrast, intercropping with *S. alfredii* did not significantly affect soybean biomass, but resulted in increased Cd concentration in the soybean plants. Similar to this result, in the intercropping model of *S. nigrum* and *Cyphomandra betacea*, the growth of *Cyphomandra betacea* seedlings was inhibited (Lin et al., 2018). The research found that compared with monoculture, intercropping with *S. alfredii* increased the Cd concentration of cauliflower (Sahito, 2020). It might be attributed to differential rhizosphere interactions among plant species, which could significantly influence both plant growth dynamics and heavy metal uptake efficiency (Pishchik et al., 2002; Gai et al., 2024). The root secretions of different plant species were different, which in turn affect the soil bacterial community (Feng et al., 2024; Zhi et al., 2025), and both plant growth and the absorption of heavy metals were closely related to the soil bacterial community (Vasiliadou and Dordas, 2009; He et al., 2024). In intercropping conditions, the number of

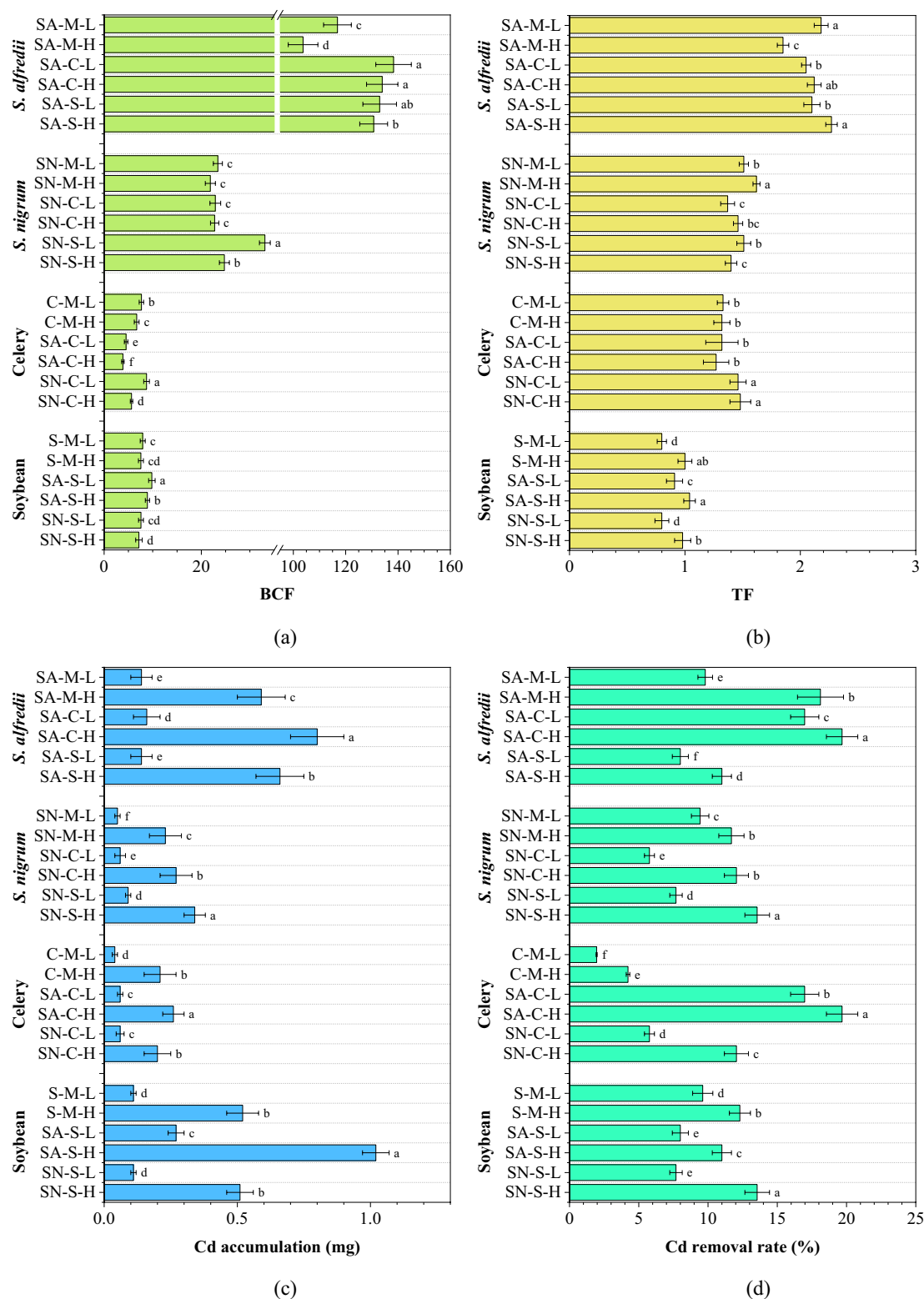


FIGURE 7

Bio-concentration factor (a), translocation factor (b), Cd accumulation (c) and Cd removal rate (d) of plants under different planting patterns (dry weight).

$\delta$ -Proteobacteria in the soil was negatively correlated with the Cd concentration in the above-ground parts of plants (Chowdhury and Bakri, 2006), and Streptomyces in the soil could produce

indoleacetic acid to promote plant growth (Khamna et al., 2010). In addition, rhizosphere nutrition was also a major factor affecting plant growth, specifically, *S. alfredii* could activate phosphorus in

the rhizosphere region (Huang et al., 2013). This study suggested that rhizobial nitrogen fixation in soybean plants, coupled with phosphorus mobilization, and might contribute to enhanced crop growth and Cd absorption in the intercropping system.

In this study, intercropping with celery and soybean led to an increase in the above-ground biomass of *S. nigrum*, while the biomass of *S. alfredii* intercropped decreased. This was similar to some research results (Bian et al., 2017; Cid et al., 2020). It might be due to the rapid growth of crops has occupied the growing space of *S. alfredii* and competed for limited soil nutrients in the intercropping system, consequently inhibiting *S. alfredii* growth (Zeng et al., 2019). Compared with *S. alfredii*, *S. nigrum* had a faster growth rate and thus was not affected by intercropping. In the monoculture treatment, the concentration and accumulation of Cd in *S. alfredii* were significantly higher than those in *S. nigrum* ( $p < 0.05$ ), indicated that in the tested soil conditions, *S. alfredii* had a stronger ability to absorb and accumulate Cd. In the intercropping model, the crop species affected the absorption of Cd by hyperaccumulators, especially in the intercropping models of *S. alfredii*-celery and *S. nigrum*-soybean, the absorption of Cd by hyperaccumulators was significantly enhanced ( $p < 0.05$ ). In the intercropping model, corn has a significant promoting effect on the Cd absorption of *S. alfredii* (Zhang C. et al., 2023; Zhang Z. et al., 2023). In this study, the intercropping of *S. nigrum* and soybean significantly increased the absorption of Cd ( $p < 0.05$ ), while the intercropping of *S. nigrum* and celery showed no significant difference in the absorption of Cd. The alterations in the rhizosphere soil environment were attributed to the intercropping systems, with these modifications being mediated by both root exudates and rhizosphere microbial communities (Cao et al., 2020; Pu et al., 2025).

## Impact of planting patterns on soil pH and Cd concentration

Soil pH critically influenced Cd availability and migration by governing both the surface charge of soil particles and the speciation of  $\text{Cd}^{2+}$ , thereby determining its transfer capacity (Luo et al., 2020; Shokalu et al., 2023; Zhang C. et al., 2023; Zhang Z. et al., 2023). Compared with monoculture systems, intercropping between crops and hyperaccumulators resulted in a gradual decrease of soil pH. The root exudates of hyperaccumulators can acidify the soil (Yang et al., 2006), as low-molecular-weight organic acids (e.g., oxalic and malic acid) release  $\text{H}^+$  ions upon dissociation (Tao et al., 2019), lowering soil pH. Compared with the monoculture of soybean, there was no significant difference in soil pH in the *S. alfredii*-soybean intercropping system. Studies demonstrated that intercropping *S. alfredii* with Chinese cabbage did not significantly affect soil pH (Ma et al., 2020), it might have occurred because Chinese cabbage grew faster than the hyperaccumulator, establishing dominance in the intercropping system and consequently reducing the impact of hyperaccumulator root activity on soil properties. Alternatively, the organic acids secreted by hyperaccumulators in this intercropping system might have been primarily utilized by soil microorganisms as nutrient sources (Xiao et al., 2020; Chi et al., 2025), leaving inadequate residual organic acids to induce soil acidification.

The root exudates of hyperaccumulators enhanced Cd migration efficiency in soil and improved plant Cd absorption (Hou et al., 2018).

Studies demonstrated that available Cd concentration in soil increased linearly with decreasing pH (Kama et al., 2024). In acidic conditions, elevated  $\text{H}^+$  concentrations reduced soil adsorption capacity for Cd, thereby converting it into bioavailable forms (Huang et al., 2024). In the present study, hyperaccumulator cultivation resulted in negative correlations between soil pH and both total Cd ( $-0.09$ ) and available Cd ( $-0.12$ ) concentrations, though the correlation was not significant ( $p > 0.05$ ) (Table 4). This might be attributed to the relatively low Cd concentrations in the experimental soil, combined with strong Cd absorption capacity of the hyperaccumulators, leading to faster Cd adsorption than activation by root exudates; and soil acidification activated absorbable Cd in the soil, which subsequently enhanced hyperaccumulator Cd absorption (Hu et al., 2013).

## Effects of planting patterns on Cd translocation in plants

The bioconcentration factor (BCF) and translocation factor (TF) are key indices for evaluating a plant's capacity to accumulate and transport heavy metals from soil. Higher the values of the indices, stronger the Cd absorption and translocation abilities. As shown in Figures 7, 8, both *S. alfredii* and *S. nigrum* exhibit high BCF and TF values ( $\text{BCF} > 10$ ,  $\text{TF} > 1.0$ ) in different planting patterns, confirming their suitability for remediating Cd-contaminated soils. Comparative analysis reveals that *S. alfredii* demonstrates even higher BCF and TF values than *S. nigrum*, suggesting superior Cd accumulation and translocation efficiency. The reason might be that the root cells of *S. alfredii* had a lower retention effect on Cd, and the xylem loading was more efficient (Liu et al., 2015). It supposed that *S. alfredii* minimized Cd accumulation in root vacuoles, facilitated faster cytoplasmic transfer and subsequent upward translocation. However, current research on the remediation potential of *S. alfredii* remains limited, further investigation to elucidate its underlying mechanisms is needed.

In this study, the BCF and TF of *S. alfredii* significantly increased ( $p < 0.05$ ) in the intercropping with celery, while those of celery decreased. It indicated that this planting model promoted the absorption and transport of Cd in the soil by *S. alfredii* and inhibited the absorption and transport of Cd by celery, which was similar to the previous research results (Wang et al., 2020). Intercropping of *Sonchus asper* with *Vicia faba* increased the BCF and TF of *Sonchus asper* from 0.90 and 0.86 in monoculture to 1.43 and 1.13 respectively, while reducing the BCF and TF of *Vicia faba* from 1.00 and 0.85 in monoculture to 0.75 and 0.66, respectively (Zhan et al., 2016). The results showed no significant difference in the BCF and TF of *S. nigrum* when intercropped with celery ( $p > 0.05$ ), and this observation might be attributed to the substantial biomass of *S. nigrum*, which led to a dilution effect on Cd concentration in plant tissues.

## Remediation efficiency and optimal planting pattern selection for Cd-contaminated soil

The appropriate intercropping system effectively reduced Cd absorption and translocation in crops while enhancing Cd absorption and

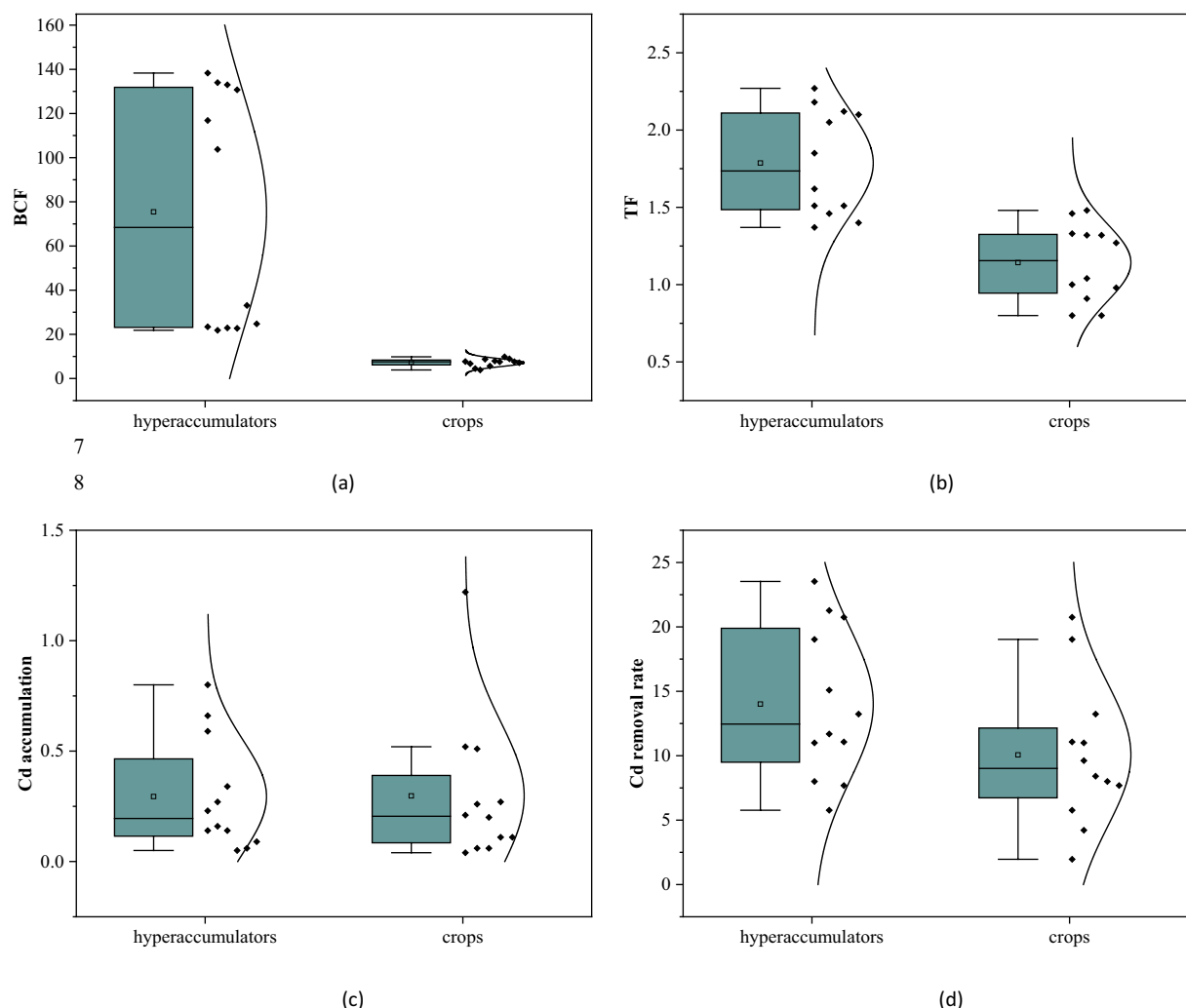


FIGURE 8

Box of bio-concentration factor (a), translocation factor (b), Cd accumulation (c) and Cd removal rate (d) of hyperaccumulators and crops under different planting patterns (dry weight).

translocation by hyperaccumulators, achieving simultaneous safe crop production and phytoremediation in Cd-contaminated soils (Ariyachandra et al., 2023; Saldarriaga et al., 2023). Studies shown that the accumulation of Cd in *S. alfredii* varies significantly in different regions, up to 1,400 mg kg<sup>-1</sup> and 97 mg kg<sup>-1</sup> Cd in shoots in Zhejiang Province and Hunan Province plants were recorded, respectively (Deng et al., 2007). In this study, the two hyperaccumulators exhibited differential Cd accumulation capacities: *S. alfredii* demonstrated superior Cd uptake compared to *S. nigrum* (Figures 4, 7). Among all tested intercropping systems, the *S. alfredii*-celery system showed the highest Cd removal rate from soil, followed by the *S. nigrum*-soybean system. The results indicated that the *S. alfredii*-celery and *S. nigrum*-soybean intercropping systems represented suitable phytoremediation approaches for Cd-contaminated farmland in the central Han River Basin. This model has the advantages of high efficiency and low risk, and it has significant promotion value for the remediation of Cd-contaminated soil and agricultural production. This study adopted the pot experiment method, which has limitations. In the future, field experiments will be conducted to better verify the remediation effect of plants on heavy metals.

## Conclusion

In the typical farmland moisture soil of the central Han River Basin, the capacity for Cd absorption and accumulation was higher in *S. alfredii* than in *S. nigrum*. In the intercropping system of *S. alfredii* and celery, the biomass of *S. alfredii* was not affected, while the biomass of celery was significantly higher compared to the monocropping ( $p < 0.05$ ). Meanwhile, *S. alfredii* exhibited enhanced Cd absorption and translocation to above-ground tissues, indicating that intercropping facilitates both Cd uptake by hyperaccumulators and the growth of associated crops. In high-Cd soil treatment, the accumulation of Cd in plants was significantly higher than that in low-Cd soil treatment ( $p < 0.05$ ). The choice of crop species in intercropping treatments influenced the absorption of Cd by the hyperaccumulators, especially in the *S. alfredii*-celery and *S. nigrum*-soybean intercropping treatments, the biomass of crops increased, the absorption of Cd by the hyperaccumulators was significantly enhanced ( $p < 0.05$ ), and the Cd removal rates from the soil were relatively high.

Therefore, the two intercropping systems of *S. alfredii* with celery and *S. nigrum* with soybean represent suitable phytoremediation models for Cd-contaminated farmland soils in the central Han River Basin. These systems effectively combine Cd enrichment with safe agricultural production, thus achieving simultaneous soil remediation and crop security.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

KY: Writing – original draft, Methodology, Investigation. XF: Software, Formal analysis, Writing – original draft. HX: Writing – original draft, Formal analysis, Investigation. JD: Data curation, Supervision, Validation, Writing – review & editing. KL: Funding acquisition, Conceptualization, Writing – original draft. YS: Investigation, Validation, Writing – review & editing. YL: Data curation, Conceptualization, Writing – review & editing.

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## Conflict of interest

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