

A Field Study on the Uptake of Cd by *Phytolacca americana* L. (pokeweed) Supplied with Nitrogen and Organic Fertilizers in Red Soil Regions

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Abstract

Application of fertilizers to enhance cadmium phytoextraction in light to moderately Cd-contaminated agricultural soils has become an increasingly common strategy. A randomized complete block design was used to examine Cd uptake and assess Cd accumulation by *Phytolacca americana* L. (pokeweed) treated with ammonium sulfate (AS treatment), urea (UR), organic fertilizer (OF) and no fertilizer (CK) under field conditions. The maximum aboveground dry biomass of 53.71 g, 51.40 g, 46.78 g and 39.36 g was recorded for the AS, UR, OF and CK treatments, respectively, within approximately 90 days and the biomass was in the order of leaf > stem > root for each treatment. No significant difference was almost observed in biomass between the four treatments at the current application rates. The Cd concentration in leaves was the highest for AS, UR, CK and OF with 31.64 mg/kg, 20.54 mg/kg, 16.70 mg/kg and 12.09 mg/kg, respectively. With regard to Cd concentration, leaves were significantly higher in AS than in the other treatments, stems displayed significant differences between AS and OF at three harvests and roots showed no significant difference between all treatments. The highest BCF and TF values were 16.36 and 2.44 for CK, 10.46 and 2.44 for OF, 19.26 and 2.54 for UR, and 31.14 and 3.67 for AS, respectively. The supply of ammonium sulfate significantly increased the BCF compared to CK. There was no significant difference in TF between all treatments. The highest level of Cd accumulation in pokeweed reached 1.34 mg/plant in the AS treatment and was 2.6 times higher than in the CK in the about 90 days, suggesting that pokeweed could be used as a tool plant for phytoremediation of Cd-contaminated farmlands in red soil regions.

Highlights

- Pokeweed produced a total biomass of 61.9 g DW/plant within 90 days.
- Ammonium sulfate application promoted significantly higher Cd uptake by pokeweed than other fertilizers.
- Ammonium sulfate fertilized pokeweed reached a Cd concentration of 22.6 mg/kg in the whole plant.
- Pokeweed had BCF 28.2 and TF 3.7 and Cd accumulation 1.34 mg/plant.
- Pokeweed could be used for phytoremediation of Cd-contaminated farmland in red soil regions.

1. Introduction

Contamination of agricultural soils by heavy metals has long been a threat to soil quality, food security and human health (Wang et al., 2019; Suhani et al., 2021). Cadmium (Cd) is considered to one of the most toxic heavy metals (Genchi et al., 2020). Cd-contaminated farmland in China accounts for 20% of the total agricultural area (Rafiq et al., 2014). Various remediation techniques and enhancement strategies have been proposed and tested to address this challenging issue (Boparai et al., 2011; Vasudevan et al., 2011; An et al., 2015; Tang et al., 2016).

Phytoremediation is a cost-effective and environmentally friendly technique to remove heavy metals from soil using plants, especially hyperaccumulator species (Raskin et al., 1997; Mahar et al., 2016). To improve the efficiency of phytoextraction, chemical additives and biological agents have been used for phytoremediation practices of Cd enriched soils (He et al., 2015; Guo et al., 2017). However, application of different fertilizers to enhance cadmium phytoextraction has become an emerging common approach (Cheng et al., 2017; Yang et al., 2019).

The effects of nitrogen fertilizers on Cd uptake by plant species have been studied (He et al., 2015; Yang et al., 2019; Wu et al., 2021). It has been reported either from hydroponic or pot experiments that the supply of nitrogen fertilizers, including $\text{NH}_4^+\text{-N}$ and/or $\text{NO}_3\text{-N}$, was able to increase Cd accumulation (Cd content/plant) in frequently studied Cd-hyperaccumulator plants, such as *Sedum alfredii* H. (Zhu et al., 2010), *Sedum plumbizincicola* (Hu et al., 2013), *Solanum nigrum* (Yang et al., 2019; Yang et al., 2022), *Rorippa globosa* (Turcz.) Thell (Wei et al., 2015), *Bidens pilosa* (Dai et al., 2020). The efficiency of Cd extraction from soils depends on its concentration in plant tissues and biomass (Jacobs et al., 2019; Cui et al., 2021). However, for the Cd-hyperaccumulators studied, there was no consistent relationship between Cd concentrations (mg/kg DW) and Cd accumulations in their shoots and roots. This phenomenon may be attributed to the dilution effect resulted from an increased biomass production (Olsen, 1983; Rodríguez-Ortíz et al., 2006).

Nevertheless, some studies have shown a simultaneous increase in terms of both Cd accumulation and Cd concentration in the Cd hyperaccumulator *Phytolacca americana* (Wang et al., 2019), the halophytic plant *Carpobrotus rossii* (Cheng et al., 2017), the cash crop tobacco (Rodríguez-Ortíz et al., 2006), the vegetable lettuce (Florijn et al., 1992), the forage grass *Italian ryegrass* (Ji et al., 2020) and the ornamental plant *Tagetes patula* (Ye et al., 2019), which were supplied with nitrogen fertilizers.

Organic fertilizers not only serve as a good source of plant nutrient in agricultural practices (Hamid et al., 2019a; Okoroafor et al., 2022), but have also been increasingly used for the purpose of phytoremediation in Cd-enriched soils (Hamid et al., 2020). A great deal of previous research into organic fertilizers immobilizing soil Cd has been reviewed by Hamid et al. (2020). In the case of Cd hyperaccumulator plants, Yang et al. (2019) reported that *Solanum nigrum* showed a significant decrease in Cd concentrations in roots and shoots when supplemented with animal manure and commercial organic fertilizer. On the other hand, a significant increase in Cd concentration was observed in roots of *Sedum alfredii* when applied with pig manure compost, but no effect was observed in shoots (Xiao et al., 2017). In another pot experiment, Addai et al. (2023) also showed that poultry litter compost increased Cd and Pb uptake in lettuce (*Lactuca sativa* L). In general, the effect of organic fertilizers on Cd mobility and bioavailability in soil may depend on the Cd adsorption, pH value and microbial reduction processes in the soil where plants grow (Chen and Cutright, 2002; Tlustoš et al., 2006; Elouear et al., 2016; Yuan et al., 2021).

Phytolacca americana L. (pokeweed) is considered as a promising Cd (hyper)accumulator plant (Yan et al., 2009; Liu et al., 2010; Liu et al 2015). It is a semi-succulent perennial herbaceous plant characterized

by high aboveground biomass, rapid growth, favorable adaptability and environmental benignity (Li et al., 2018; Liu 2015; Zhao et al., 2011) and therefore has a great potential for phytoextraction from Cd-contaminated farmland and rare-earth-element enriched mine sites (Liu et al., 2020).

Several pot or hydroponic studies (Yan et al., 2009; Liu et al., 2010; Wang et al., 2019) have demonstrated that pokeweed has a strong capacity to take up Cd from soil, with shoot Cd concentration reaching up to $637 \text{ mg}\cdot\text{kg}^{-1}$ and bio-concentration factor (BCF) and translocation factor (TF) ranging from 4 to 10 and 1 to 3, respectively. Furthermore, the plant grown in the natural habitat, where soil Cd concentration was $1,083 \text{ mg}\cdot\text{kg}^{-1}$, had its leaf Cd concentration of up to $402 \text{ mg}\cdot\text{kg}^{-1}$ (Liu et al., 2010).

Our previous pot experiment (Wang et al., 2019) showed that the application of ammonium sulfate and urea as nitrogen sources can all significantly increase the aboveground Cd concentration of pokeweed. However, litter information on Cd uptake and accumulation by the Cd-stressed plant under farmland conditions is lacking, and it appeared that no field experiment had been conducted to investigate the effect of fertilizer application on Cd uptake from farmland soils.

The objectives of this study were: 1) to determine the Cd uptake by pokeweed in Cd-contaminated farmland; 2) to examine the enhancement of Cd accumulation using commercial nitrogenous and organic fertilizers, and 3) to evaluate the phytoextraction of the plant as a phytoremediation tool in Cd-contaminated farmland.

2. Materials and Methods

2.1. Plant material

The seeds of *Phytolacca americana* L (pokeweed) used for this study were collected from its cultivated population at the Hengxi Research Base (118.762156° E, 31.867210° N) of Nanjing Institute of Environmental Sciences, Nanjing and the wild population grows in the subtropical mountainous regions of central and southern China.

Seeds were washed with tap water, immersed in 65% (by mass fraction) concentrated nitric acid for 10 min, removed out and washed with ultrapure water (Milli-Q, an electrical conductivity of $18.2 \text{ M}\Omega\cdot\text{cm}$). Plastic seedling plates containing 72 cells (9cm deep) each were prepared for seed germination. Each cell was filled to a height of 7–8 cm with commercial substrate, sown with 3–5 seeds and covered with approximately 1cm of the same substrate. All seeded plates were placed in a greenhouse established adjacent to the experimental field, kept at an air temperature of $25 \sim 30^\circ\text{C}$ and often watered frequently to ensure that the substrate in all cells was moist.

2.2. Experimental site and design

The experimental site was located in the red-soil-dominated Fujiang Township (114.292547°E, 25.442301°N), Dayu County, Southern China, which belongs to the subtropical humid climate zone, with

the average annual temperature and precipitation of 18.5°C and 1,563 mm, respectively, the annual sunshine of 1499.3 hours, and the annual frost-free period of 301 days.

The experiment was conducted from April to September, 2019 in an abandoned Cd-contaminated farmland, from which an experimental area of approximately 1,000 m² was selected for this study. A randomized complete block design was used. The whole experimental area was divided into three blocks, with each block containing four plots of 5m×6m. In addition, four 3m-wide border rows were established around the outer blocks and 30 cm wide ditches between plots were dug for drainage and management.

Before the plots were split, a five-point blended soil sample was taken from the cultivated layers (0–20 cm) in each block using the S-type sampling method to determine the average values of the selected soil chemical properties (Table 1). The pH, organic matter, total N, total P and total K were measured by usual methods (Lu, 2000).

Table 1
Soil chemical properties, the information and application rates of fertilizers used.

Soil			Fertilizers		
Parameters	Units	Values	Types	Key nutrients	Rates at each time (kg/plot)
Total Cd	mg/kg	0.80	Ammonium sulfate	N ≥ 21%	2
pH		4.64	Urea	N ≥ 46%	1
OM	g/kg	21.80	Organic fertilizer	Total nutrients ≥ 4%; OM ≥ 45%	2
Total N	mg/kg	1231			
Total P	mg/kg	857			
Total K	mg/kg	15623			
OM: Organic matter; N: Nitrogen; P: Phosphorus; K: Potassium; Total nutrients: N + P ₂ O ₅ + K ₂ O					

The experiment consisted of four treatments in each block: CK with no fertilizer as control, AS fertilized with commercial ammonium sulfate, UR with commercial urea and OF with commercial organic fertilizer. Background information on the fertilizers was presented in Table 1. According to the fertilization practice for local crops, the application rate for each fertilizer at each time was given in Table 1. The first and second applications were by hand made 2 days before and 40 days after the seedling transplanting, respectively. Weed management in the field followed local crop practice.

On 25–26 May, 2019, approximately 10cm long seedlings were transplanted into the plots, including the border rows, at a density of 180 plants or so per plot and a row spacing of 40 cm. The seedlings that died within 3 days were replanted and not afterward.

2.3. Plant harvest and analysis

The plant material was harvested once on June 14 and 28, July 14 and 28, and August 30, 2019. Six plants in each plot were randomly selected and harvested at each time, with careful collection of roots. Roots, stems and leaves of all harvested plants were separated with scissors and the roots were washed with tap water to remove visible soil particles and blotted with tissue paper. The materials harvested in each plot were placed in three plastic bags by leaf, stem or root and taken to the laboratory within 24 hours. The fresh materials were washed with ultrapure water in laboratory, oven dried at 105°C for 0.5h and then dried at 70°C to constant, weighed, ground, and sieved through a 2-mm nylon sieve for Cd determination.

The plant samples were digested using a microwave digester (Mars 6, CEM, USA) and total Cd was determined using an inductively coupled plasma mass spectrometer (ICP-MS, Thermofisher, USA). Additionally, a blank sample and a certified standard substance (GSB – 6) were digested and analyzed simultaneously, resulting in recovery rate of 93.2% for total Cd.

2.4. Statistical analysis

Data in this study were statistically analyzed by one-way ANOVA using SPSS ver. 24.0 (Statistical Package for Social Science for Windows, ver. 24.0). Tukey's honest significant difference (HSD) post-hoc test at $P < 0.05$ was used to test for significance of plant biomass and Cd content. Origin 9.0 package was used to generate graphs.

3. Results

3.1. Effect of fertilization on biomass of pokeweed

Throughout the study, the pokeweed plants sown in all the experimental plots grew well and exhibited no toxic symptoms. For all four treatments, the biomass (DW) of the plant leaf, stem and root increased over time and reached a maximum at the last harvest (Fig. 1), with aboveground and total dry matter of 53.71 g and 61.87 g, 51.40 g and 63.86 g, 46.78 g and 56.17 g, 39.36 g and 46.16 g for the AS, UR, OF and CK treatments, respectively. Plant biomass at each harvest was in the order of leaf > stem > root for each treatment (Fig. 1).

No significant difference ($P > 0.05$) was observed in the biomass of the leaves, stems and roots among the four treatments, except that the leaf biomass in the UR was significantly higher ($P < 0.05$) than that in OF and CK at the second harvest and the stem biomass in the UR was significantly higher than that in OF at the fourth harvest (Fig. 1).

3.2. Change in Cd concentrations in plant tissues with time of exposure to Cd

As shown in Fig. 2, the Cd concentration in the plant leaves increased progressively with exposure time, reaching the highest value of 31.64 mg/kg, 20.54 mg/kg and 16.70 mg/kg occurring at the last harvest for the AS, UR and CK treatments, respectively and of 12.09 g/kg at the fourth harvest for the OF. In contrast to the leaves, Cd concentrations in roots showed a rapid increase on from 14 to 28 June and then a slight decreasing trend. Variation pattern of the stem Cd concentration in AS was similar to that of its root, but there was some fluctuation in the UR, OF and CK, with a coefficient of variability of 0.20, 0.46, 0.17 and 0.20 for AS, UR, OF and CK, respectively. The Cd concentration was higher in leaves than in either roots or stems after the first harvest.

3.3. Effect of fertilization on Cd uptake by pokeweed

Effect of fertilization on Cd uptake by pokeweed was shown in Fig. 3. After the first harvest, the Cd concentration in the leaves of the AS treatment was significantly higher ($P < 0.05$) than in the other treatments, except for no significant difference ($P > 0.05$) between AS and UR at the second and fourth harvests.

Significant difference in Cd concentrations of the stems was observed between both AS and OF treatments at the second, third and last harvests. There was no significant difference in Cd concentration of the roots for all treatments during the whole experiment.

Effect of fertilization on Cd concentrations in the aboveground parts and the whole plant were similar to that in the leaves, suggesting that ammonium sulfate displayed the strongest enhancement of Cd uptake by pokeweed over the other fertilizers.

3.4. Effect of fertilization on BCF and TF of Cd in Pokeweed

The BCF value (Cd concentration in shoots / Cd concentration in soil) of pokeweed were presented in Table 2. The BCF of the plant showed an increasing trend with time for all treatments, ranging from 3.44 to 16.36 for CK treatment, 4.95 to 10.46 for OF, 3.98 to 19.26 for UR, and 6.22 to 31.14 for AS. One way ANOVA showed that the BCF of the plant applied with ammonium sulfate was significantly higher ($P < 0.05$) than that of the CK, except for the first harvest where no significant difference ($P > 0.05$) in BCF was observed among all treatments. At the last harvest, the BCF for AS was 2.98, 1.90 and 1.62 times that of the OF, CK and UR treatments, respectively. No significant difference in BCF was found between OF, CK and UR during this experiment, with the exception of the last harvest where the BCF for UR was significantly higher than for OF.

Table 2
BCF and TF of Cd uptake by pokeweed.

	June 14		June 28		July 14		July 28		Aug. 30	
	BCF	TF	BCF	TF	BCF	TF	BCF	TF	BCF	TF
AS	6.22± 2.31 a	1.47± 0.37 a	16.64± 4.34 a	1.83± 0.46 a	21.23± 5.64 a	1.99± 0.22 a	21.21± 6.28 a	2.31± 0.41 a	31.14± 5.02 a	3.67± 0.86 a
UR	3.98± 1.13 a	1.25± 0.09 a	9.90± 1.41 ab	1.16± 0.38 a	11.12± 2.35 b	1.42± 0.43 a	14.79± 5.62ab	1.95± 0.79 a	19.26± 0.37 b	2.54± 0.73 a
OF	4.95± 1.37 a	0.80± 0.13 a	8.36± 2.62 b	1.08± 0.12 a	10.60± 1.69 b	1.58± 0.27 a	11.60± 2.93 ab	2.03± 0.16 a	10.46± 4.18 c	2.44± 0.59 a
CK	3.44± 0.90 a	0.92± 0.33 a	7.09± 1.19 b	1.04± 0.31 a	10.08± 0.35 b	1.61± 0.25 a	8.13± 1.41b	1.55± 0.10 a	16.36± 0.78 bc	2.44± 0.60 a
Data are presents as mean ± S.E. (n = 3). Different letters in columns indicate significant differences at P < 0.05.										

For all treatments, the TF value (Cd concentration in shoots / Cd concentration in roots) of the plant had a similar dynamic pattern to BCF with time and were higher than 1, with a maximum of 2.44 for CK treatment, 2.44 for OF, 2.54 for UR and 3.67 for AS. No significant difference in TF was observed between all treatments (Table 2).

The level of Cd accumulation in pokeweed steadily increased over time, ranging from 1.7 µg/plant to 1336.9 µg/plant for the AS treatment, 1.1 µg/plant to 787.8 µg/plant for the UR, 0.7 µg/plant to 415.9 µg/plant for the OF, and 0.4 µg/plant to 510.3 µg/plant for the CK. At the last harvest, the Cd accumulation in the AS plants was 2.62 times higher than in the CK.

4. Discussion

4.1. Biomass production

In the present study, no significant increase in shoot and root biomass of the pokeweed plant supplied with three fertilizers was found in comparison with CK. This result seemed to disagree with some pot experiments conducted with other Cd hyperaccumulator plants (Wu et al., 2021).

Yang et al. (2020) and two other research groups (Yang et al., 2019; Yang et al., 2021) reported that the biomass of shoots and roots of *S. nigrum*. was significantly higher for (NH₄)₂SO₄ and urea treatments

than for the unfertilized control. Similar results were also documented for other plant species supplied with $(\text{NH}_4)_2\text{SO}_4$ or urea, such as *B. pilosa* (Dai et al., 2020), *R. globosa* (Turcz.) Thell (Wei, et al., 2015), *Thlaspi caerulescens* (Monsant et al., 2008). In addition, Ji et al. (2020) found that shoot biomass of Italian ryegrass (*Lolium multiflorum* Lam.) treated with urea were increased by up to 213.37% in the first year and 38.15% in the second year.

However, our result was also consistent with several studies that showed that the addition of urea did not significantly influence the biomass production for *C. rossii* grown in a Cd-spiked soil (Liu et al., 2016) and two *Sedum* species planted in pots with the Cd-enriched soil collected from local lead smelters (Guo et al., 2017). Furthermore, Lin et al. (2019) even found that the shoot biomass of Cd hyperaccumulator *S. alfredii* after NH_4NO_3 addition was significantly lower than the control (no fertilizer) by 38% and decreased with its increasing addition.

The previous findings and our present result, that the effect of N application on plant biomass varied widely may be due to the fact that plant species have different requirements for the dose and forms of N (Hu et al., 2013; Liu et al. 2015). Our present result was probably attributed to the N application rate not being sufficient to produce an additional pokeweed growth compared to the unfertilized treatment, based on our previous study and the experimental design that: (1) in a pot experiment, the biomass of pokeweed supplied with N at 400 mg/kg as $(\text{NH}_4)_2\text{SO}_4$ or urea increased by 165.3% and 150.4% respectively, compared to the no N control (Wang et al., 2019); (2) the current N rate was determined by local agricultural practice for crops that may have different N requirements than pokeweed.

Consistent with no effect of organic fertilizer on the pokeweed growth (Fig. 1), Cahill et al. (1999) showed that the plant had no difference in root biomass in a pot experiment for nutrient heterogeneity when grown in soil amended with a commercial dehydrated cow manure and in background soil (no manure) (Cahilljr and Casper, 1999). However, Yang et al. (2019) found a significant increase in the biomass (roots and shoots) of *S. nigrum* treated with two chicken and pig manures and a commercial organic fertilizer compared to the unfertilized control. Therefore, it is necessary to carry out further field studies on effects of organic fertilizers on the biomass production of the plant under Cd stress, especially in terms of their application rates and types.

4.2. Fertilizer application and Cd uptake

Our field experiment showed that pokeweed had a good Cd uptake (24.9mg/kg DW and 22.6 mg/kg of Cd concentrations in its shoots and whole plant, respectively, recorded in the AS treatment) from the Cd-contaminated farmland soil (0.80 mg/kg of Cd), although the concentration was lower in comparison with the data documented by several researchers. Their results showed that when pokeweed grew healthily in Cd-containing medium, they recorded different Cd concentrations in shoots, ranging from 31.2 mg/kg DW (when pokeweed was grown in pots where soil contained 35 mg/kg Cd for 90 days) (Yan et al., 2009), 63.0 mg/kg or so (in pots with 10 mg/kg Cd for 10 weeks) (Liu et al., 2015), 100.4 mg/kg (in pots with 10 mg/kg Cd for 90 days) (Wang et al., 2019) up to 116 mg/kg (in solution with 10 μM Cd for 10 days) (Liu et al., 2010).

Our result indicated that supply of $(\text{NH}_4)_2\text{SO}_4$ can significantly increase Cd uptake by pokeweed under field conditions, as observed in our pot experiment with the plant (Wang et al., 2019) and reported in a number of studies for wild and domesticated plant species using the same fertilizer (review by Yang et al. 2019). However, some studies found that there was no significant difference in root and shoot Cd concentrations between $(\text{NH}_4)_2\text{SO}_4$ treatment and no fertilizer control for several Cd hyperaccumulator plants, such as *S. nigrum* (Yang et al., 2019) and *pilosa* (Dai et al., 2020).

As with the effect of urea on Cd uptake, it appeared to have little effect on Cd uptake by the pokeweed in this study. The previous studies had also mixed results in this regard. Wei et al. (2015) found that urea-treated *R. globosa* (Turcz.) Thell did not increase Cd concentrations in its shoots and roots as compared to the unfertilized control. In contrast, Mitchell et al. (2000) showed that Cd concentrations in durum wheat increased with increasing N application rate to 800 $\mu\text{g/g}$ as urea.

Normally, plants take up NH_4^+ to release H^+ into the root zone, leading to an acidified rhizosphere and consequently an increased Cd bioavailability (Wu et al., 2021; Zaccheo et al., 2006). Wang et al. (2020) reported that soil pH in Cd-enriched rice soils treated with $(\text{NH}_4)_2\text{SO}_4$ was 0.18 units lower than the control (urea) and claimed that the anion SO_4^{2-} probably contributed to the change in soil pH. Cheng et al. (2017) also found that the rhizosphere solution pH (4.15 to 4.88) of *C. rossi* treated with $(\text{NH}_4)_2\text{SO}_4$ was lower than that of the bulk soil (4.45 to 5.22), but there was no significant difference in pH for *S. nigrum* treated with urea (Yang et al., 2019). Likewise, a pot experiment showed that pH of the rhizosphere of *T. caerulea* grown in a zinc-contaminated soil was significantly lower relative to the no chemical addition when treated with $(\text{NH}_4)_2\text{SO}_4$, but no difference when treated with urea (Monsant et al., 2008).

In addition, NH_4^+ can also cause desorption of Cd from exchange sites or soil colloids through ion exchange (Lorenz et al., 1994). Therefore, increased Cd uptake by plants when supplied with NH_4^+ -based nitrogen fertilizers depends not only on plant species but also on the physical and chemical properties of the soil where they grow.

According to our presently available data, it may be difficult to assess whether fertilization with $(\text{NH}_4)_2\text{SO}_4$ under field conditions leads to a more acidic rhizosphere and/or a stronger Cd desorption, resulting in the highest Cd uptake by the pokeweed in the AS treatment compared to the other treatments.

Regarding the effect of organic fertilizer Cd uptake, this field experiment showed that OF treatment had no significant effect on Cd concentrations in the shoot and root of pokeweed (Fig. 3). Some studies reported that organic fertilizer application had an enhancing effect on availability (Sanchez-Marin et al., 2010) and mobility (Clemente et al., 2010) of some heavy metals. In contrast, other studies indicated that organic fertilizer supply can significantly reduce Cd concentrations in the shoots and roots of *S. alfredii* treated with composted pig manure (Lin et al., 2020) and *nigrum* treated with chicken manure, pig manure, and commercial organic fertilizer (Yang et al., 2019). These findings and our present result indicate that

metal availability and stabilization are related to organic sources, soil physicochemical properties, and metal type and amount (Khan et al., 2017).

4.3. Potential for phytoremediation of Cd-contaminated soils

The indices of both BCF and TF are well established criteria for assessing the uptake and translocation of heavy metals by hyperaccumulator plants. If the BCF and TF of a plant species are both greater than 1, it can be considered as a candidate hyperaccumulator for a heavy metal (Kacalkova et al., 2015). This study showed that the pokeweed was comparable in terms of BCF and TF (Table 2) to several hyperaccumulators, such as *S. alfredii* (BCF: 63, TF: 2.2) (Ma et al., 2020), *S. plumbizincicola* (BCF: 41) (Cui et al., 2016), *S. nigrum* (BCF: 8.7, TF: 1.4) (Ji et al., 2011) and *Viola baoshanensis* (BCF: 4.8) (Zhuang et al., 2007).

Furthermore, pokeweed produced dry matter of 61.87 g DW/plant in the AS and 63.85 g DW/plant in the UR during about 90 days (Fig. 1), which is remarkably higher than the previous results from the pot experiments by several authors, who recorded 2.34 g/plant of *S. alfredii* (Chen et al., 2022), 0.38 g/plant of *T. caerulea* (Monsant et al., 2008) and 2.4 g/plant of *B. pilosa* L (Dai et al., 2020). Our current study indicates that pokeweed has relative advantages in high biomass and rapid growth and thus can be used as a tool plant for phytoremediation of a large area of Cd-contaminated farmland in red soil regions.

5. Conclusions

- (1) In Cd-contaminated farmland soil, pokeweed produced a total biomass of 61.9 g/plant within 90 days and the current application rate of ammonia sulfate, urea or bio-organic fertilizer had no significant effect on its biomass increase, suggesting that insufficient application rate may be an important consideration.
- (2) In comparison to the other fertilization treatments, the Cd concentration of 22.6 mg/kg in the ammonium sulfate fertilized plant was significantly higher than in the urea, bio-organic fertilizer or no fertilizer treatments, indicating that the application of ammonium sulfate is able to promote more Cd uptake by pokeweed.
- (3) Pokeweed has a greater potential for phytoremediation of light to moderately Cd-contaminated agricultural land in red soil regions due to its relatively higher biomass, BCF and TF values of 28.2 and 3.7, respectively, and the good Cd accumulation of 1.34 mg/plant.

Declarations

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Ethics approval

Not applicable

Consent to Participate

Not applicable

Consent to publication

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Authors' contributions

Formulating ideas: Zhenhua Zhang, Cigang Yu, Qi Wang, Changyong Wang, Wei Tian

Designing experiment: Zhenhua Zhang, CigangYu, Qi Wang

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Conflict of interest: All authors declare that there are no conflicts of interest.

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Figures

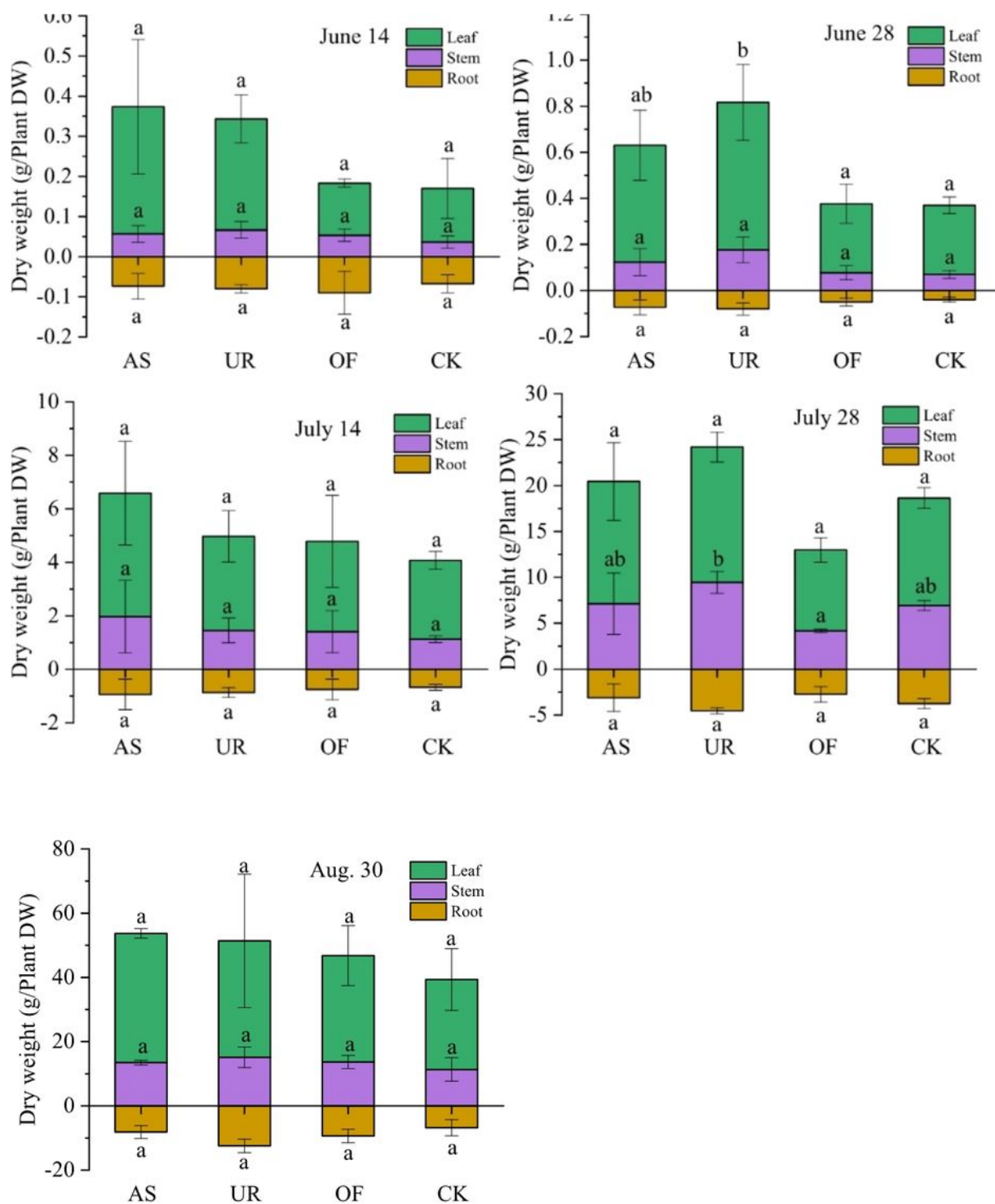


Figure 1

Effect of fertilization on plant biomass.

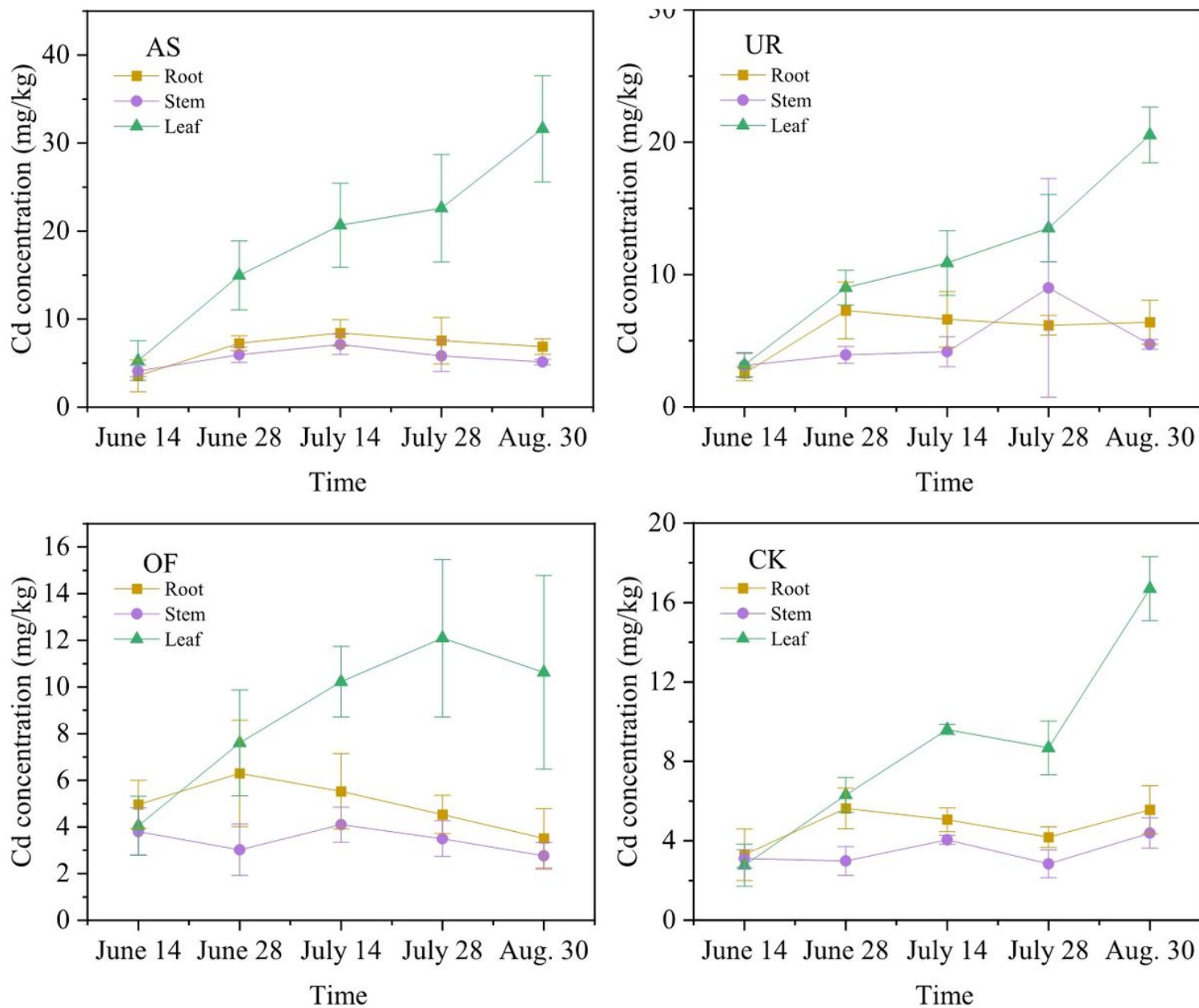


Figure 2

Change in Cd concentrations in plant tissues with time.

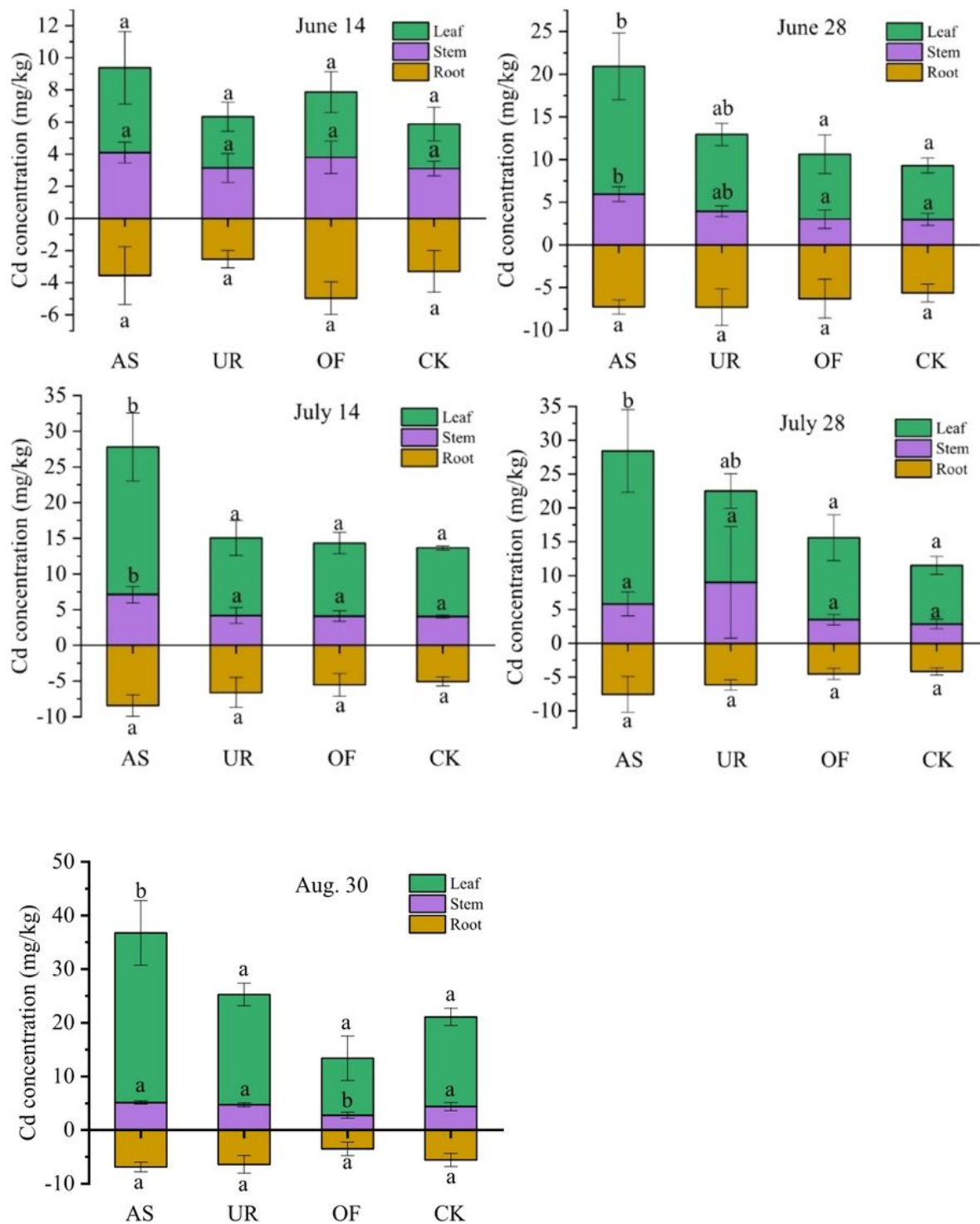


Figure 3

Effect of fertilization on Cd concentrations in plant tissues.