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Phytoremediation of arsenic contaminated soil based on drip irrigation and intercropping

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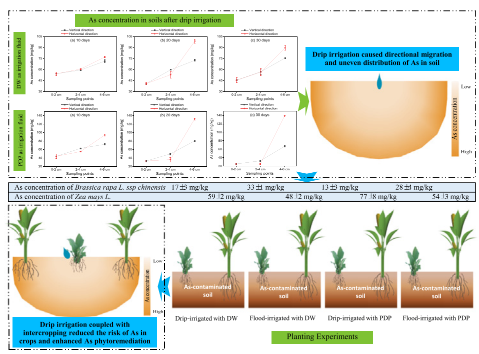
HIGHLIGHTS

- Arsenic (As) in soil showed a directional migration under drip irrigation.
- Added KH_2PO_4 in drip irrigation solution promoted As migration in soil.
- These effects plus intercropping reduced As in crops and soils.

GRAPHICAL ABSTRACT



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ABSTRACT

A directional leaching in drip irrigation along with intercropping was developed for enhanced phytoremediation of soils contaminated with arsenic (As). Spatiotemporal variations of As levels in soil and effects of irrigation eluents on As migration were analyzed in drip irrigation. Moreover, accumulated levels of As in *Zea mays* L. and *Brassica rapa* L. ssp. *chinensis* (the intercropping species) under drip irrigation and flood irrigation were compared to evaluate the enhancement on phytoremediation by drip irrigation. Results showed that As exhibited a directional migration in soil under drip irrigation, in which the solution of potassium dihydrogen phosphate (PDP) as the eluent significantly promoted As directional migration in soil. Compared to the flood-irrigated intercropping treatments, the As levels in crops (*Brassica rapa* L. ssp. *chinensis*) decreased significantly and that of remediating plants (*Zea mays* L. seedlings) increased significantly under the drip-irrigated intercropping condition. Drip irrigation coupled with intercropping dramatically reduced the risk of As contamination in crops and improved the phytoremediation of As-contaminated soil. PDP further enhanced the disparate effect of drip irrigation on As accumulation by crops and remediation plants.

1. Introduction

Arsenic (As) is one of these hazardous metalloids with carcinogenicity and teratogenicity (Prakash et al., 2021; X. Wang et al., 2021; Young-Shin et al., 2016). Arsenic may enter the soil either by natural processes (e.g., weathering of As-rich minerals and volcanic activity) or via anthropogenic activities (e.g., mining, smelting and uses of wood preservatives, As-based fertilizers and pesticides, and irrigation with As-contaminated groundwater) (Abbas et al., 2018; Punshon et al., 2017). Pollution by As in farmland is widespread in the world (Dittmar et al., 2010; Spanu et al., 2012; Wei et al., 2021; Xie and Cheng, 2021), which causes a decrease in soil quality, deterioration of the ecosystem, reduction of crop production, and risk in food safety (Su et al., 2009; Yuan et al., 2021). At present, there are many exploratory engineering technologies in the remediation of heavy metal contaminated farmlands and industrial lands, such as solidification/stabilization

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and ex-situ chemical extraction (Vithanage et al., 2012). These technologies are appropriate for heavily polluted areas but they easily destroy the function of soil (Hettick et al., 2015; Song et al., 2022). Phytoremediation is an in-situ technology with a broad application prospect on the remediation of contaminated soil (Hettick et al., 2015; Wang et al., 2011), with advantages of low energy consumption, low investment cost and environmental sustainability. Phytoremediation of heavy metal contaminated soil has a strong theoretical and practical feasibility, although there are disadvantages of a long cycle (Debiec-Andrzejewska et al., 2020). This technology is still in the developing stage compared to other engineering technologies that have been applied in large scale up to now.

There is a conflict between agricultural production and phytoremediation of contaminated farmlands especially for low and medium pollution areas (Vithanage et al., 2012). As an agrarian technology, intercropping can improve crop yield/quality and offer other economic and social benefits (Q. Wang et al., 2021; Zhou et al., 2021). For example, intercropping hyperaccumulators with cash crops could lower the contents of heavy metals in soil and hence the levels in crops, and then by harvesting the aboveground parts of hyperaccumulators the total heavy metal contents in contaminated farmlands would be decreased (Wan and Lei, 2018). Intercropping with different plants to repair heavy metal contaminated soils has been studied. For example, *A. donax* L. and *B. papyrifera* L. are used for Pb-contaminated soil (Zeng et al., 2019), *Zea mays* L. and Japan Clover Herb for Cd-contaminated soil (An et al., 2011). It was reported intercropping *Pteris vittata* and *Morus alba* can increase the As concentration in *Pteris vittata*, achieving a better remediation effect on As-contaminated soil (Wan et al., 2017; Wan and Yang, 2018). The method of intercropping hyperaccumulators with crops provides incentives for remediating As-contaminated soils while harvesting agricultural products that meet standards. However, there is a risk that the water and fertilizer levels in farmland will decline due to the competitive uptake of hyperaccumulators, which will eventually lead to a decline in crop yield (Yang et al., 2017). At the same time, the repair efficiency of this method still needs to be strengthened. These disadvantages restrict the application potential for plant intercropping technology in the remediation of heavy metal contaminated soil. Thus, it is necessary to develop more assistive measures and intercropping plants to further improve the efficiency of phytoremediation.

Soil washing technology has been successfully applied to the remediation of heavy metal contaminated soil (Kocar et al., 2006). The principal mechanisms are to use reagents to react with heavy metals in the soil solid phase to form soluble heavy metal ions and thus release the pollutants out of the soil (Bruss Ea U et al., 2015). Phosphate is a vital substance for crops and a common soil leaching solvent, which has the characteristic of pollution-free. It can decrease the uptake of As by soil components by adjusting pH or ion-exchanging to achieve the remediation of polluted soil (Zeng et al., 2012). Previous report showed that among various potassium and sodium salts, potassium phosphate was most effective in extracting As, attaining >40 % extraction at pH = 6–8 with a minimum damage to the soil properties (Alam et al., 2001). Some researchers evaluated the arsenate (As(V)) sorption capacities of six soils with different properties. Addition of P decreases the As(V) sorption by different soils to different extents and consequently makes As more available (Zeng et al., 2012).

Drip irrigation is a widely used water-saving irrigation technology in arid and semi-arid areas. In farmland, water is always infiltrating the soil during drip irrigation, which leads to a leaching effect of the heavy metal from contaminated soil. Because water diffuses spatially under drip irrigation, the soil will form a hemispherical wetted body with more water near the dripper and less water around it (Cote et al., 2003). This special leaching process by water may lead to the regular and uneven distribution of heavy metals in soil. The addition of leaching solvent in irrigation solution may accelerate the dissolution and migration of heavy metals in soil (Xue et al., 2021). The combination of drip irrigation and intercropping may have a synergistic effect on phytoremediation of heavy metal contaminated farmland soil, and hence reduce the level of As in crops at the same time. At this time, little research has been focused on it by our knowledge.

The intercropping combinations selected in this experiment are *Brassica rapa* L. ssp. *chinensis* (the crops) and *Zea mays* L. (the remediation plants). The As accumulation ability of *Brassica rapa* L. ssp. *chinensis* is weaker than that of *Zea mays* L., and it needs more water to grow, thus *Brassica rapa* L. ssp. *chinensis* is suitable to plant in the center of the wetted body (Rosas-Castor et al., 2014a; Rosas-Castor et al., 2014b; Xiao et al., 2009). Although *Zea mays* L. has a lower As accumulation capacity than that of *Pteris vittata* or other hyperaccumulators, the growth speed of *Zea mays* L. straw and its biomass are much larger than that of other hyperaccumulators. At the same time, the accumulation of As in *Zea mays* L. grain is lower than those in wheat and rice grain, which makes it possible to obtain economic benefits when *Zea mays* L. is used in the remediation of low As-contaminated soil (Adomako et al., 2011). Some researchers have found that *Zea mays* L. is proper for substitution planting in As-contaminated farmland (Cao et al., 2019). Moreover, *Zea mays* L. has a good drought resistance and can be planted in the soil on the edge of the wetted body (Rosas-Castor et al., 2014a; Yang et al., 2020).

In the present study, the objectives are (i) to investigate the temporal and spatial variation characteristics of As in soil under drip irrigation; (ii) to test the effects of soil eluents (potassium dihydrogen phosphate) on directional migration of As in the soil; (iii) to study the synergistic effect of drip irrigation and intercropping on phytoremediation of As-contaminated soil.

2. Materials and methods

2.1. Chemicals

All chemicals used in this work were of analytical grade; they were used without further purification. All water solutions of chemicals were prepared using deionized water (18.2 MΩ).

2.2. Soil preparation

The soil was collected from the Kuitun Reclamation Area in Xinjiang, China (84°21′18″–84°36′27″ E, 44°52′48″–45°05′41″ N). Kuitun is located in the south of Junggar Basin at the northern foot of Tianshan Mountains, with low-lying terrain. As bearing minerals in the Tianshan Mountains provide a source of As. The groundwater in Kuitun is known to be contaminated with a natural As level as high as 800 μg L^{-1} (Chen et al., 2018). The high-As groundwater was used as a drinking water source before 1980s, which resulted in an endemic As poisoning. Because of the wide application of drip irrigation in Kuitun farm lands in 2000s and the reclamation of a large uncultivated land, an increasing volume of high-As groundwater was then utilized for irrigation (Chen et al., 2018). A long-term use of this water could elevate the As levels in agricultural soils and subsequently in food sources. Previous researches showed that the As content in 0-50 cm soil in this area ranges from 7.25 to 75.28 mg kg^{-1} (Luo et al., 2007).

The soil was air-dried, ground, passed through a 2 mm sieve, and mixed as evenly as possible. The basic physical and chemical properties of the soil were described as follows: pH 7.61 ± 0.25; cation exchange capacity (CEC) 6.42 ± 0.33 mmol/kg; organic matter content 26.30 ± 1.02 g/kg; total organic carbon (C), total nitrogen (N), total phosphorus (P), and total potassium (K) contents are 15.30 ± 0.51 g/kg, 1.65 ± 0.13 g/kg, 0.77 ± 0.03 g/kg, and 21.30 ± 0.70 mg kg^{-1}, respectively. The soil particle-size classification is listed in Table 1.

2.3. Drip irrigation experiments

The experimental soil was filled into a pot with a height of 12 cm and a diameter of 13 cm. A special flow-controlled device was assembled for drip

Table 1
Soil particle-size classification.

Particle-size (mm)	<0.002	0.002–0.02	0.02–0.2	0.2–2
Proportion (%)	20.44	32.60	13.16	33.60

irrigation, and the dripper was set at the center of the soil surface. Deionized water (DW) and 2 mM potassium dihydrogen phosphate (PDP) solutions were used as irrigation solutions respectively. The measured flow rate was 2 mL min^{-1}, and each irrigation volume was 35 mL. The experimental soil was drip-irrigated twice a day, in the morning and evening. Soil samples were collected after being drip-irrigated for 10 days, 20 days and 30 days, respectively.

2.4. Planting experiments

The experimental soil was packed into polyvinylchloride (PVC) pots (45 cm × 17 cm × 15 cm in length, width and depth) and each pot with 7.00 kg of soil. The soil was intercropped with *Zea mays* L. and *Brassica rapa* L. ssp. *chinensis* and the intercropping model is shown in Fig. 1. The *Brassica rapa* L. ssp. *chinensis* was drip-irrigated with DW and PDP, respectively, while the control group was flood-irrigated. The measured discharge rate was 2 mL min^{-1}, with the irrigation volume set at 35 mL each time and with three replications for each treatment.

Experiments were conducted in a natural indoor environment in the campus of Xinjiang University in Urumqi, China, and the plants grew for 50 days in the summer of 2020 without supplementary illumination under a daytime temperature range of 20–30 °C and a night temperature range of 18–25 °C.

2.5. Sample collection and extraction of As

2.5.1. Drip irrigation experiment

Soil samples were collected from both vertical and horizontal directions of wetted soil bodies. The regions of 0–2 cm, 2–4 cm and 4–6 cm below the dripper were designated as A1, A2 and A3 sampling points, respectively. With the dripper as the center point, the regions of 0–2 cm, 2–4 cm, and 4–6 cm away from it in the horizontal were designated as the B1, B2 and B3 sampling points (A1 and B1 being the same). The final sample was obtained using established quartering techniques, dried, and sieved by 100-mesh before analysis. Subsamples were weighed (0.1 g) into quartz glass digestion tubes and then digested using a nitric acid procedure. Three milliliters of nitric acid were added to each tube and allowed to stand overnight. The tubes were then placed on a heating block with the temperature raised to 60 °C. When the temperature was gradually raised from 60 °C to 140 °C within 2 h, samples were continuously digested for about 20 h. The sample with a little solution was cooled, filtered through a filter paper, and then diluted in deionized water and made up to 50 mL.

Considering that the mobility of As is largely affected by the chemical fractions of the soil, the optimized "BCR" sequencing extraction was carried out to identify the speciation of As in the soil samples of different treatments in this research (Sutherland and Tack, 2002). The details are listed in the SI.

2.5.2. Planting experiment

After growing for 50 days, *Brassica rapa* L. ssp. *chinensis* and *Zea mays* L. were harvested and carefully washed 2–3 times with tap water, deionized water, and high purity water in sequence. The plant samples were dried at 105 °C for 30 min, and then oven-dried at 70 °C until a constant weight was obtained. Samples were then passed through a 100-mesh nylon sieve after being ground and then digested with nitric acid. At the same time, the rhizosphere soil samples of the *Brassica rapa* L. ssp. *chinensis* (Y1), the rhizosphere soil samples of the *Zea mays* L. (Y2), and the non-rhizosphere control soil samples (Y3) were collected for pretreatment and digestion.

2.6. Sample analysis

Samples were consistently determined using AFS-PF3 single-channel atomic fluorescence spectrometer (Beijing Puxi General Instrument Co., Ltd.). The determination method was according to the literature report (Chen et al., 2018).

2.7. Quality control

For quality control, the reagent blank and standard reference samples were digested and determined simultaneously. Standard reference samples, such as soil sample (GBW07426) and As standard solution (100 mg L^{-1}), were provided by National Standard Substances Center. Meanwhile, the spiked experiment was used to test the accuracy of plant sample analysis. The average of calculated recoveries of reference soil samples was 92 ± 1 %, and the spiked recoveries of plant samples were 97 ± 5 %. All the detected concentrations of samples were corrected by the corresponding recoveries.

3. Results and discussion

3.1. Directed migration of As in soil under drip irrigation

By observations of wetted soil bodies, we found that the experimental soil formed a hemispherical shape with a radius of about 6.3 cm (Fig. 2). Wetted soil bodies were shaped by water migration, allowing water to leach As species in the wetted soil. The sampling range can be judged according to the shape of the wetted body. At a prolonged drip irrigation time, both vertical and horizontal water diffusion in wetted soil bodies gradually slowed down (Fig. 3).

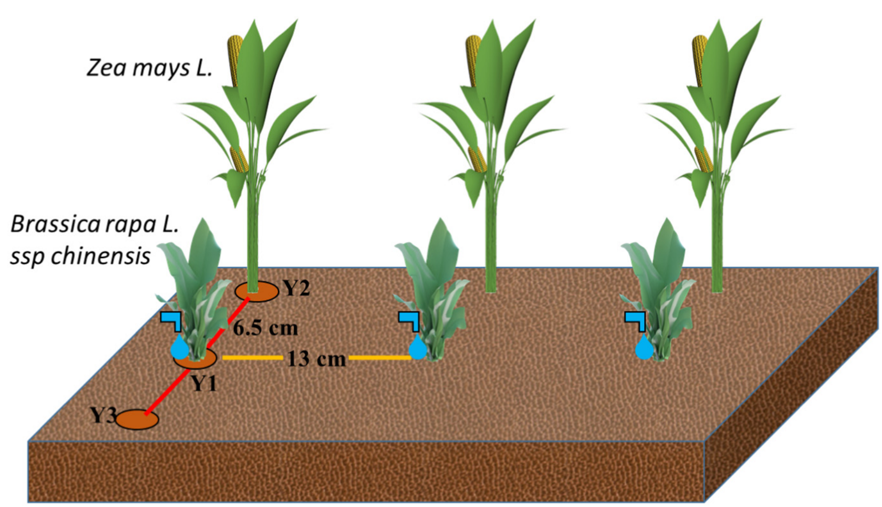

Fig. 1. Schematic diagram of the intercropping.

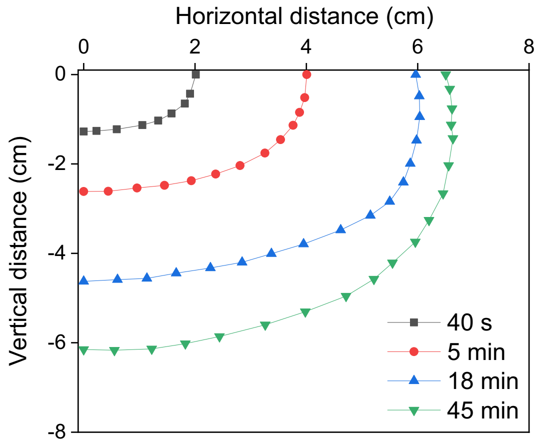

Fig. 2. Migration of the wetting front, with the four lines depicting the boundary of the wetted soil body formed by the movement of water in soil after different times of drip irrigation.

The initial As concentration in the experimental soil was 66 ± 1 mg kg^{-1}. After being drip-irrigated by DW for different periods (10, 20 and 30 days), all the wetted bodies showed the characteristics of reduced As in the soil near the dripper and increased As in the soil far from the dripper. These characteristics were more significant in the horizontal direction (Fig. 4). After 30 days of drip irrigation, the As levels in the soils 0-2 cm away from the dripper decreased to 41 ± 1 mg kg^{-1}, while the levels in soils 2-4 cm and 4-6 cm away from the dripper increased to 73 ± 1 mg kg^{-1} and 99 ± 3 mg kg^{-1} respectively. The results showed an obvious As directional migration and uneven distribution in topsoil with drip irrigation. Arsenite (As(III)) and arsenate (As(V)) are the most abundant forms in soil, with As(III) being 10 times more soluble and mobile than As(V) (Larios et al., 2013). In oxygen-rich environments and well-drained soils, As (V) dominate (as $H_2AsO_4^-$ in acidic soils and $HAsO_4^{2-}$ in alkaline ones) whereas under reducing conditions, such as regularly flooded soils, As(III) is more stable (Van Herreweghe et al., 2003). Therefore, the fraction of more mobile As might increase during drip irrigation. In the process of drip irrigation, the movement of water in soil exhibited a three-dimensional divergence (Ben-Asher et al., 1986). Directional migration of As might be caused by the continuous leaching of water. As desorbed from the inner part of the wetted soil continuously moved along the migration direction of water, and became resorbed to the soil away from the dripper. The repeated desorption-sorption processes along the water movement direction made the As level in soil changing regularly with the drip irrigation times. At the same time, some As species might return to the soil surface by a capillary effect and were washed to the edge of the wetted surface (Chen et al., 2022; Ren et al., 2022; Zhou et al., 2022).

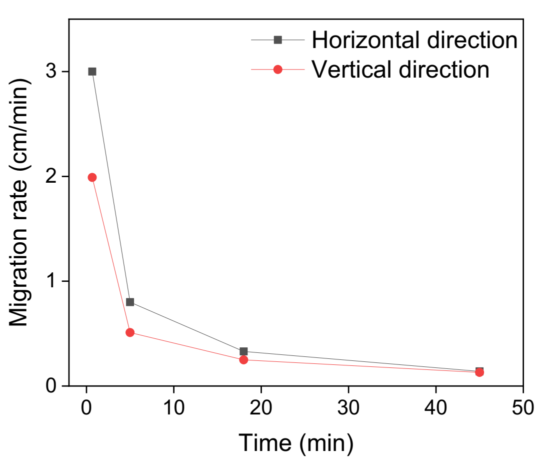

Fig. 3. Changes of the water spreading rate in soil with time in horizontal and vertical directions.

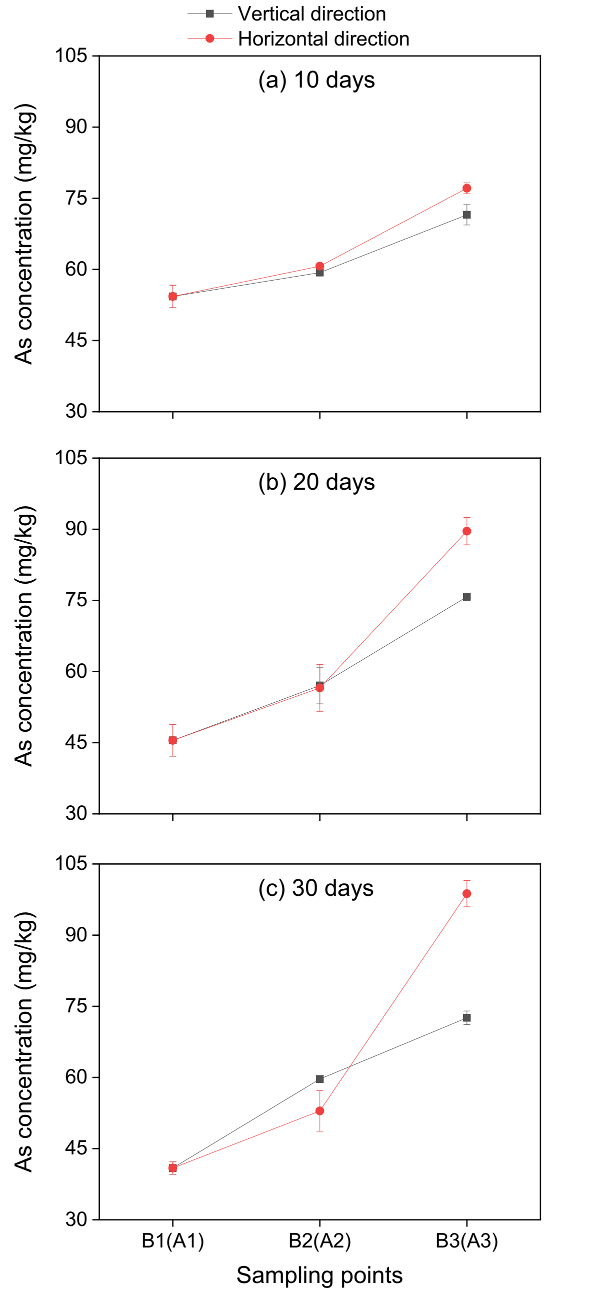

Fig. 4. As concentrations in soil at different sampling points after drip-irrigated with DW for 10 days (a), 20 days (b) and 30 days (c). B1(A1): sampling points in the area 0–2 cm away from the dripper; B2(A2): sampling points in the area with a vertical distance of 2–4 cm from the dripper; B3(A3): sampling points in the area with a vertical distance of 4–6 cm from the dripper. The bars indicate standard errors of the means from three repetitions.

3.2. The influence of PDP on directional migration of As in soil

A similar migration and distribution mode of As was found in the wetted soil body drip-irrigated with PDP solution. Moreover, the temporal and spatial variation of As level in wetted soil bodies was more significant than that with DW (Fig. 5). The results showed that adding PDP to drip irrigation solution could intensify the directional migration and inhomogeneous distribution of As in soil, especially in the horizontal direction. As and phosphorus (P) belong to group V elements with similar chemical properties and

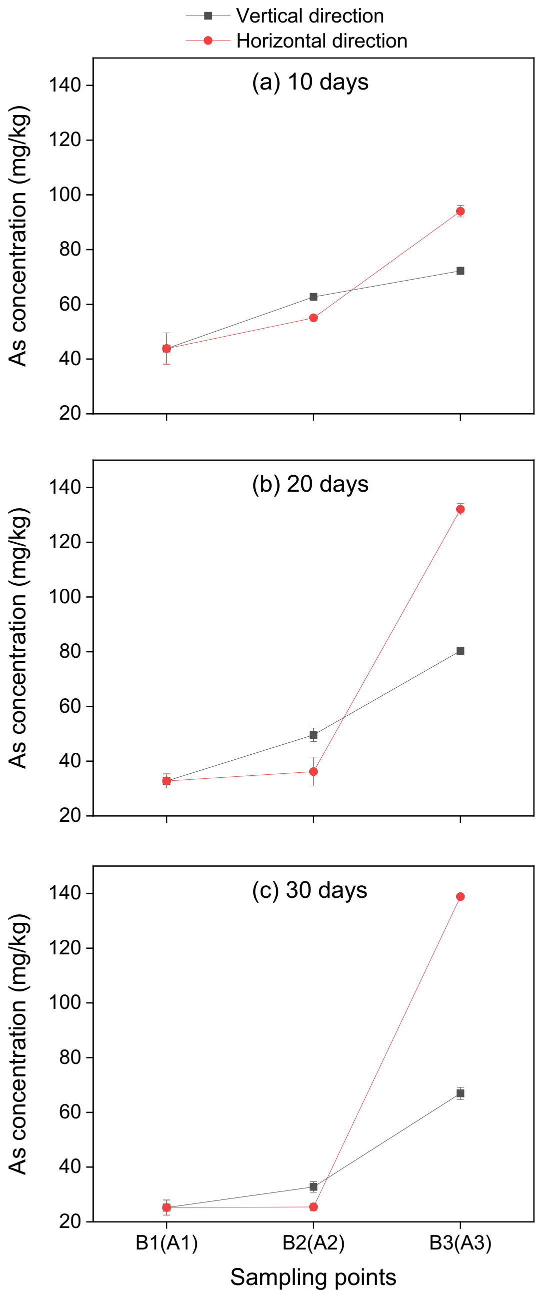

Fig. 5. As concentrations in soil at different sampling points after drip-irrigated with PDP for 10 days (a), 20 days (b) and 30 days (c). B1(A1): sampling points in the area 0–2 cm away from the dripper; B2(A2): sampling points in the area with a vertical distance of 2–4 cm from the dripper; B3(A3): sampling points in the area with a vertical distance of 4–6 cm from the dripper. The bars indicate standard errors of the means from three repetitions.

behaviors (Larios et al., 2013). P can compete with As for reactive sites in soils and consequently increase the mobility and availability of As (Qafoku et al., 1999). Drip-irrigated with PDP solution, not only As(III) could dissolve and migrate, PO_4^{2-} in solution could also interact with soil (Melamed et al., 1995; Zeng et al., 2012). P might act as a competitive species with As(V) and consequently suppressed the adsorption of As (V) in soil. Therefore, more As was dissolved into the solution and migrated to the edge of the wetted body with leaching. This result was consistent with those of Zhang and Selim, who found that the adsorption of As (V) decreases significantly when the P level in soil solution increases (Zhang and Selim, 2008).

In the sequential extraction experiment, the addition of PDP to drip irrigation solution promoted the migration of exchangeable As and reducible As, supporting the effect of P on the dissolution of weak-binding As in soil (Table S1).

3.3. Variation of As migration rate in soil under drip irrigation

With prolonged drip irrigation times, As migrated farther away from the dripper while the migration rate decreased. The addition of PDP to irrigation solution promoted the migration of As rapidly in a short time, but the enhancement effect decreased gradually (Table 2). As reported, there are various forms of As in soil, including water-soluble As, exchangeable As, insoluble As and bound As (He et al., 2021). Water-soluble and partially exchangeable As can be extracted from soil by water, while the other two forms are difficult to be released by water (Lee et al., 2021). In the early stage of drip irrigation, the fraction of mobile As in soil near the dripper was high but decreased with the drip irrigation frequency or volume, which resulted in a decreasing mobility of As in soil.

The supplemental analysis of As components confirmed the directional movement of As under drip irrigation (Table S1). With increased drip irrigation times, the amounts of acid extractable, reducible and oxidizable As in soils near the dripper decrease, while those away from the dripper increased. The levels of residual As changed slightly and irregularly. In the process of drip irrigation, the As weakly bound to soil should be subject to a greater migration. The dissolution and migration of reducible As and oxidizable As may be related to the changes of soil redox environment caused by irrigation (Van Herreweghe et al., 2003). The high exchangeable proportion of As in soil may be related to the fact that the source of As is mainly from irrigation input (Chen et al., 2018).

Many As sorption-desorption processes might cause a delayed effect on As migration, making As migration rate at sites A1/B1 much higher than that at sites A3 and B3. The regular changes of As migration indicated that As distribution in topsoil could be regulated, controlled, forecasted and managed artificially by adjusting the properties, quantity, and flow rate of the drip irrigation solution. Drip irrigation may thus become a valuable auxiliary technology of phytoremediation through appropriate management.

3.4. Effects of drip irrigation and intercropping on As uptake by plants

After being flood-irrigated with DW or PDP solution for 50 days, there was no significant difference of As levels in soils collected from sites Y1,

Table 2
Variation of As concentrations and As migration rate (mg kg^{-1} day^{-1}) at different sampling points after drip-irrigated for different times. A1/B1: sampling points in the area 0–2 cm away from the dripper; A3: sampling points in the area with a vertical distance of 4–6 cm from the dripper; B3: sampling points in the area with a horizontal distance of 4–6 cm from the dripper.

Irrigation liquid	Time (days)	A1/B1		A3		B3	
		Reduction of As	Emigration rate	Increase of As	Immigration rate	Increase of As	Immigration rate
DW	10	18 %	1.21	8 %	0.51	16 %	1.07
	20	32 %	1.05	14 %	0.47	35 %	1.16
	30	38 %	0.85	8 %	0.21	49 %	1.08
PDP	10	34 %	2.26	9 %	0.58	42 %	2.76
	20	51 %	1.68	21 %	0.70	99 %	3.28
	30	62 %	1.37	0.8 %	0.02	109 %	2.41

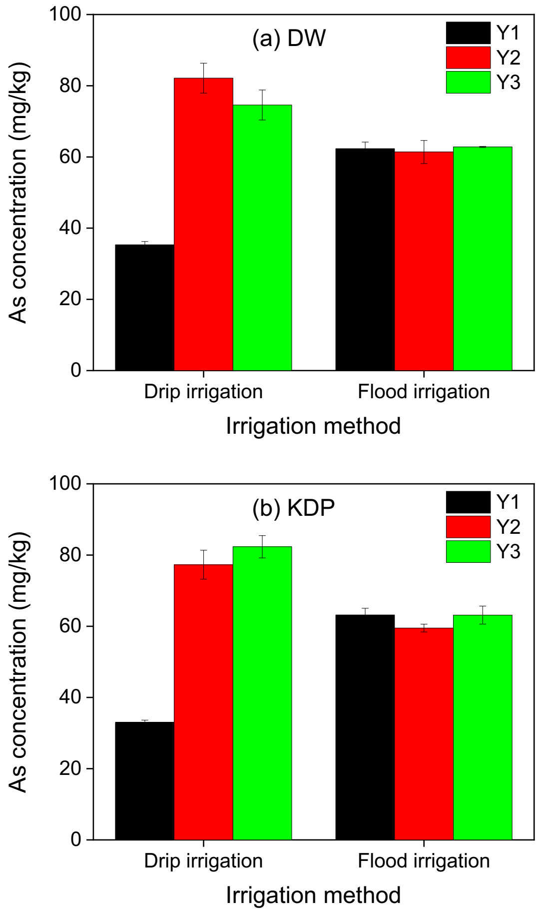

Fig. 6. As concentrations in rhizosphere soil of *Brassica rapa* L. ssp. *chinensis* (Y1), rhizosphere soil of *Zea mays* L. (Y2), and non-rhizosphere control soil (Y3) irrigated by either drip irrigation or flooding irrigation. (a): DW as the irrigation liquid; (b): PDP as the irrigation liquid. The bars indicate standard errors of the means from three repetitions.

Y2 and Y3 in each treatment (Fig. 6). When drip-irrigated with DW or PDP solution, there was no obvious difference between the As levels in soils collected from sites Y2 and Y3, while As levels in soils from Y1 were significantly lower than those from Y2 and Y3 (Fig. 6). The results indicated that As in the rhizosphere soil of *Brassica rapa* L. ssp. *chinensis* migrated much more to the rhizosphere soil of *Zea mays* L. in a drip irrigation system than that in a flood irrigation system. This result was consistent with the results in Section 2.1. The As levels in the rhizosphere soil of *Zea mays* L. were not less than that in the control soil without plants (Fig. 6). The higher concentration of As in *Zea mays* L. rhizosphere soil may be related to the promoted As migration by plant roots (Rosas-Castor et al., 2014b; Wan et al., 2017). *Zea mays* L. was planted on the edge of the wetted body that was relatively arid. The uptake of water by *Zea mays* L. promoted the movement of water in the wetted body, and the As dissolved in the drip irrigation solution could also migrate to the rhizosphere soil and become accumulated.

Compared with the flooding irrigation system, the As level in *Brassica rapa* L. ssp. *chinensis* decreased and that in *Zea mays* L. increased in the drip irrigation system (Table 3). After being drip-irrigated by DW, the As level in *Brassica rapa* L. ssp. *chinensis* decreased by 48 % and increased by 23 % in *Zea mays* L. When drip-irrigated by PDP solution, the As level in *Brassica rapa* L. ssp. *chinensis* decreased by 54 % and increased by 41 % in *Zea mays* L. Because of the directional leaching of drip irrigation, As in the rhizosphere of *Brassica rapa* L. ssp. *chinensis* migrated to the rhizosphere of *Zea mays* L. so that *Zea mays* L. could absorb more As and reduce As accumulation in *Brassica rapa* L. ssp. *chinensis*. This proved that compared with the traditional methods, the combined drip irrigation and intercropping could strengthen the remediation efficiency of the highly accumulative plants and reduce the safety risk of edible crops.

The As level in *Zea mays* L. solution was significantly higher when drip-irrigated with PDP solution (Table 3). That indicated that adding PDP to irrigation solution could promote the absorption of As by *Zea mays* L. PDP has a strong capability to leach As from soil such that more As can be transferred to the rhizosphere soil of *Zea mays* L. Earlier studies showed that the similarity in chemical structures and properties of phosphate ion and As (V) ions enables phytoavailable P in agricultural soil to release As to *Zea mays* L. (Mallick et al., 2011). At the same time, the phosphorus nutrition status in the plant itself and the available inorganic P in the rhizosphere can strongly affect the As bioaccumulation by plants. Several studies have reported a low level of P and As has a synergistic effect on the plant absorption process which could promote the accumulation of As in plants (Gunes et al., 2009; Tu and Ma, 2003; Zheng et al., 2018). The addition of potassium dihydrogen phosphate to the irrigation solution increased the biomass of *Zea mays* L. (Table 4), which also promoted the phytoremediation efficiency.

4. Conclusions

A special directional migration of As in soil under drip irrigation was observed, in which the wetted soil body exhibited less As in the center and more As at the edges. With an increased drip irrigation time, this feature appeared more and more obvious while the migration rate of As gradually decreased. Potassium dihydrogen phosphate added to the drip

Table 3
As concentrations (mg kg^{-1} dw) of plants irrigated by either drip irrigation or flooding irrigation for 50 days.

Treatment	DW as the irrigation liquid			PDP as the irrigation liquid		
	Brassica rapa L. ssp. *chinensis*	*Zea mays* L.	ANOVA	*Brassica rapa* L. ssp. *chinensis*	*Zea mays* L.	ANOVA
Drip irrigation	17 ± 3	59 ± 2	**	13 ± 3	77 ± 8	**
Flood irrigation	33 ± 1	48 ± 2	*	28 ± 4	54 ± 3	*
ANOVA	*	*		*	*	

NS, no significant.
** $P \leq 0.01$.
* $P \leq 0.05$.

Table 4
Biomass of plants (g fw) irrigated by either drip irrigation or flooding irrigation for 50 days.

Mode	Irrigated with DW		Irrigated with PDP	
	Brassica rapa L. ssp. *chinensis*	*Zea mays* L.	*Brassica rapa* L. ssp. *chinensis*	*Zea mays* L.
Drip irrigation	9.34 ± 0.66	5.05 ± 0.21	12.04 ± 0.75	5.81 ± 0.50
Flood irrigation	6.35 ± 0.84	5.63 ± 0.42	7.75 ± 1.12	6.64 ± 0.42

solution promoted the directional migration of As in the wetted body. The distribution of As in topsoil could be controlled by adjusting the drip irrigation condition for phytoremediation of As-contaminated soil. Intercropping could further augment the differential distribution of As in soil caused by drip irrigation for remediation and utilization of As-contaminated soil. The As levels in crops decreased, while that in *Zea mays* L. seedlings for phytoremediation increased. The combination of drip irrigation and intercropping could significantly reduce the safety risk of edible crops and promote the As uptake by remediation plants. The addition of potassium dihydrogen phosphate further enhances the remediation effect of drip irrigation and intercropping on phytoremediation.

CRediT authorship contribution statement

Yuhong Su: Conceptualization. Ning Li: Methodology Writing - Reviewing and editing, Writing - Original draft, Formal analysis. Jiaohar·Hongwei: Investigation and Visualization.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157970.

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