Research article

Sorption and mobility of cadmium in soil impacted by irrigation waters

Baogui Li [a,b,1], Yuan Liu [a,1], Zhen Tao [a], Zhijuan Zhao [a], Tao Fan [a], Zhongyang Li [a,c,*]

[a] Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China
[b] College of Land Science and Technology, China Agricultural University, Haidian District, Beijing 100193, China
[c] National Research and Observation Station of Shangqiu Agro-ecology System, Shangqiu 476000, China

ARTICLE INFO

ABSTRACT

Soil contamination by Cd has drawn global attention, while how irrigation waters modulate Cd sorption and mobility in soil remains obscure. We address this by investigating how cropped sandy soil irrigated with different waters altered Cd sorption and mobility using a rhizobox experiment followed by a batch experiment. Maize were planted in the rhizoboxes and irrigated by reclaimed water (RW), livestock wastewater (LW) and deionized water (CK), respectively. The bulk soil sampled from each treatment after 60 days of growth was employed to measure the Cd sorption and mobility using the isothermal adsorption and desorption experiments. The results showed that, in a small rhizobox experiment, the adsorption rate of Cd by the bulk soil in the adsorption phase was much faster than the desorption rate in desorption phase. Irrigation with RW and LW both reduced the Cd adsorption capacity of soil, and the reducing degree brought by LW was more obvious. Cd desorption rate was very low but keep increasing in the desorption stage, and pre-RW irrigation had the potential to increase Cd desorption from soil. Although the results were obtained based on the bulk soil sampled from a rhizobox experiment, our study strongly suggests that the altered Cd adsorption and desorption behavior in the soil caused by the RW and LW irrigation may risk the farmland ecosystem and deserve more concern.

1. Introduction

Cd accumulation in soil induced by anthropogenic activities is a global environmental concern over the past two decades activities because of its toxicity to human health and detrimental impact on plant growth and soil functions [1]. Remediation of Cd-contaminated soil is crucial for food safety and sustainable agriculture, and requires a thorough understanding of the mobility and bioavailability of soil Cd. The bioavailability and mobility of Cd in agricultural soil are affected by agronomical practices like fertilization, irrigation, cropping and so forth [2–4]. Previous studies reported that soil additives (e.g. biochar, hydroxyapatite, humic acid, zeolite) are important factors that influence Cd mobility and bioavailability as they affect soil pH, ion strength, organic matter, attendant cations or anions, functional groups on the sorbent [5–8]. Water management plays a critical role in soil Cd bioavailability and mobility [9–11]. It was reported that the pore water velocity under flood irrigation affected Cd transport in a sandy loam soil with high or low salinity based on column experiments [12]. Irrigation with treated wastewater only raised the metals (Zn and Cd) sorption

---

ability of calcareous soils relative to that with the blending of treated wastewater and surface water [13]. Therefore, it is necessary to intensively study the influential mechanisms of water management on soil Cd mobility and bioavailability.

Due to the shortage of water in arid and semiarid regions, reclaimed water (RW) and even the raw wastewater were used for irrigation, which might not only aggravate soil Cd contamination, but also increase the bioavailability and mobility of Cd in soil. Generally, the content of N, P, chemical oxygen demand (COD), Cu, Zn and antibiotics is higher in livestock wastewater (LW) [14–16], while the electrical conductivity and the content of salt ions are higher in RW [17]. As a result, the properties of irrigated soil by RW and LW differed from the soil irrigated by clean water and hence altered the bioavailability and mobility of soil Cd. Unfortunately, the influencing mechanisms of irrigation with wastewater and reclaimed water on soil Cd mobility and bioavailability have not yet been studied sufficiently. In particular, the sorption and desorption of Cd in the soil irrigated with different unconventional water sources should be researched intensively to gain an insight knowledge of Cd migration at water and soil interface.

The mechanisms regarding Cd immobilization involves electrostatic attraction, cation exchange, complexation and precipitation [18]. These processes were impacted by the interaction between soil properties and Cd [19]. We hypothesized that irrigation with RW and LW results in the changes in soil properties, and hence alters the Cd(II) fixation ability of soil. To test this hypothesis, batch adsorption and desorption equilibrium experiments were employed in this study. We aimed to: (1) compare the sorption and desorption of Cd in reclaimed water- and livestock wastewater-irrigated soils with clean water-irrigated or unirrigated soils; and (2) to clarify the dominate factors controlling the distinction in retention capacity of Cd in these soils.

2. Materials and methods

2.1. Soils preparation

The soil used in the experiment was taken from the rhizobox experiment in our previous work under irrigation with different waters [20]. The soil, originated from alluvial sediments of Yellow River with a silt loam texture (sand:silt:clay = 15:79:6), is classified as Calcaric Fluvisols according to World Reference Base (WRB) [21]. The details of the rhizobox experiment were given in Ref. [20], but for completeness it was briefly explained here. The soil was taken from the top 20 cm in an experimental station irrigated with groundwater at Xinxiang, Henan province of China. The soil was air-dried and ground first, and it was then thoroughly mixed with base fertilizer consisting of urea (200 mg N kg^{-1}), calcium superphosphate (100 mg P kg^{-1}) and potassium chloride (200 mg K kg^{-1}) prior to being packed into 14 cm × 12 cm × 17 cm rhizoboxes. Each rhizobox consisted of five compartments (5:1:2:1:5) along its 14 cm side by 48 μm nylon mesh and was filled with 3 kg of soil. Three maize seeds of Jundan 20 variety were drilled into the central compartment. The rhizoboxes were irrigated with reclaimed water, livestock wastewater and deionized water (DW, control). The reclaimed water was taken from Camel Bay sewage treatment plant in Xinxiang and the livestock wastewater from the anaerobic fermentation tank at Xinxiang Shengda Animal Husbandry Co., Ltd. The water properties are given in Table S1. Prior to its use for irrigation, the livestock wastewater was diluted with deionized water at a 1:5 ratio. Each treatment has three replicates and all experiments were conducted in a greenhouse.

The maize was harvested 60 days after seedling emergence. To exclude the root-induced impact, we employed the soil from the end compartment far away from the central rhizosphere for sorption and desorption analysis. As a comparison, the original and unplanted soil (OS) were also recruited in the analysis. All the air-dried soils were ground and passed through a 0.25 mm sieve prior to the sorption and desorption experiments, and the physical and chemical properties of these soils were given in Table S2. The available Cd in the soils was at similar level. The nutrients and salt content in the soil irrigated with RW and LW was higher than that with DW. RW-irrigated soil exhibited high electrical conductivity (EC), pH and soluble Na$^+$, Cl$^-$, HCO$_3^-$ and SO$_4^{2-}$ but low organic matter (OM), soluble K$^+$, Ca^{2+} and NO$_3^-$, available Cu and available Zn, compared to LW-irrigated soil.

2.2. Sorption

The soil of 3 g was added to a 50-mL polyethylene centrifuge tube, and followed by the blend with 30 mL of mixed solution containing 0.01 M NaNO$_3$ solution as a supporting electrolyte and Cd (II) with a specific concentration (5, 10, 20, 40 or 50 mg L^{-1}) made by Cd(NO$_3$)$_2$·4H$_2$O reagent. When 0.01 mol L^{-1} NaNO$_3$ solution with no Cd(II) (0 mg L^{-1}) was used [22], Cd was almost undetectable in the solution during the whole adsorption and desorption procedures (Fig. S1), hence the effect of Cd release by the soil itself on the sorption and desorption processes in this study was regarded as negligible. After the tube was shaken at 200 rpm for 24 h at 25 ± 1 °C followed by 10 m of centrifugation at 4000 rpm, 5 mL of supernatant was pipetted out for Cd concentration analysis. Then the tube was shaken for a further 96 h, and the supernatant was also drawn for Cd concentration measurement after centrifugation. To monitor the pH of the system, the pH in the suspension with initial Cd(II) of 20 mg L^{-1} was measured using a pH meter (Orion-star A211, USA) with a pH electrode (Thermo Orion 9157BNMD, USA) during the 120 h. The concentration of Cd(II) in the supernatant was measured by an atomic adsorption spectrometry (AAS) (AA-6300, SHIMADZU, Japan), and the amount of Cd adsorbed was calculated from the following formulae:

$$S_{ads-24h} = \frac{(C_0 - C_1)V_0}{m} \tag{1}$$

$$S_{ads-120h} = S_{ads-24h} + \frac{(C_1 - C_2)V_1}{m} \tag{2}$$

where $S_{ads-24h}$ and $S_{ads-120h}$ are Cd adsorbed by the soil at 24 h and 120 h respectively after the onset of the experiment, C_0 is the concentration of Cd(II) in the prepared solution, and C_1 and C_2 are the concentration of Cd(II) in the supernatants at 24 h and 120 h after onset of experiment respectively (mg L^{-1}), V_0 (30 mL) is the volume of prepared solution added to the tube (30 mL), V_1 (25 mL) is the volume of solution remained in the tube after the first supernatant sampling, m (3 g) was the mass of the soil.

2.3. Desorption

Na$^+$ and NO$_3^-$ exerted less effect on Cd(II) adsorption compared with other cations and anions [23], and NaNO$_3$ is commonly used as the background electrolyte for the adsorption batch experiments, hence we also choose NaNO$_3$ as the background electrolyte in our study. By the way, the NaNO$_3$ concentration of 0.01 mol L^{-1} have been recommended by tremendous of studies [24,25]. The soil and the residual solution with the tube were weighed immediately after all the supernatant was carefully poured out at the end of the adsorption experiment. To begin the desorption process, NaNO$_3$ solution (30 mL, 0.01 mol L^{-1}) was added, followed by 24 h of shaking at 200 rpm. Then a 5-mL aliquot of supernatant was sampled for Cd(II) analysis and the rest was gently emptied as mentioned previously. Then the tube with the residuals was weighed and the above procedures were repeated four times to measure how much Cd could mobilize. The mobilized Cd was calculated as follows:

$$S_{des} = \sum_{j=1}^{n_2} \frac{C_j \left(V_0 + M_j - M_1 \right) - C_{j-1} \left(M_j - M_1 \right)}{m} \tag{3}$$

where S_{des} is the Cd released from soil after adsorption at different sampling time (mg kg^{-1}), C_j is the Cd(II) concentration in the solution of the jth desorption (mg L^{-1}), C_{j-1} is the Cd(II) concentration in the solution at the end of adsorption ($j = 1$) or the Cd(II) concentration in the solution of the $(j-1)$th desorption ($j = 2, 3, 4$) (mg L^{-1}), M_1 is the total weight of dry soil and tube (g), M_j are the total weight of solution residue, soil and tube before the jth addition of desorption solution, n_2 is the times of desorption solution added. The desorption ratio was calculated as follows:

$$\text{Desorption ratio (\%)} = \frac{S_{des}}{S_{ads-120h}} \times 100 \tag{4}$$

where $S_{ads-120h}$ is all Cd adsorbed by the soil measured in the adsorption process.

2.4. Adsorption models

The adsorption isotherm was described by the following Langmuir formula [26]:

$$S_{ads} = S_{max} \frac{K_d C}{1 + K_d C} \tag{5}$$

where S_{ads} is the adsorbed Cd by soil when the Cd(II) concentration in the equilibrium solution is C, K_d is distribution coefficient, and S_{max} is the maximum Cd the soil could adsorb. As a comparison, the adsorption result was fitted to the Freundlich formula [27]:

$$S_{ads} = K_f C^b \tag{6}$$
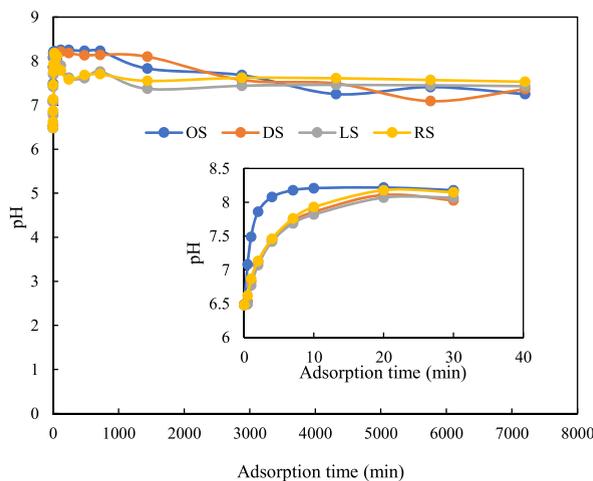
Fig. 1. Kinetics of pH of suspension at 20 mg L^{-1} of initial Cd(II) with the adsorption time. OS refers to the original soil before irrigation, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and RS represents the reclaimed water-irrigated soil.

where K_f is the distribution coefficient and b is a fitting parameter.

2.5. Statistical analysis

The difference between treatments was assessed by the analysis of variance (ANOVA) using IBM SPSS 25, and the Duncan's multiple range test was used for *post-hoc* pairwise comparisons at significant level ($p < 0.05$). Pearson correlation coefficients were used to analyze the correlations between the adsorption and desorption of Cd and soil physicochemical characteristics.

3. Results

3.1. Cd sorption

In the adsorption process, the pH reading of the reaction system shown by the pH meter increased rapidly in the first 20 min, then changed slightly between 20 min and 120 h (Fig. 1). The increase in adsorbed Cd with the initial Cd (II) concentration between different treatments were compared after 24 h and 120 h of the adsorption experiment (Fig. 2). After 24 h, more than 99.6% of Cd in the solution was immobilized, indicating that the soils were very sorptive to Cd (Fig. 2A). After 24-h reaction, the remaining Cd in equilibrium solutions in the irrigated soils was not significantly altered relative to the original soil with one exception. After 120 h, the remaining Cd in the equilibrium solution of original soil treated with 40 and 50 mg L^{-1} Cd was the lowest (Fig. 2B), indicating that the original soil was the most sorptive to Cd. Cd concentration in the equilibrium solution of the soil irrigated with deionized water was basically higher than that of the original soil, when they were treated by 5, 20, 40 and 50 mg L^{-1} Cd. The Cd concentration was the highest in the equilibrium solutions of the soil irrigated by LW when the initial Cd was >10 mg L^{-1}, demonstrating that the Cd mobility was the highest in the soil irrigated LW.

The simulation results of Freundlich and Langmuir equations matched the nonlinear Cd isotherms well (Fig. 3). A set of calculated parameters of the equations are listed in Table 1. All the correlation coefficients (r^2) in the Freundlich equations are above 0.996 and higher than those in the Langmuir equations, indicating that Freundlich equations fit the Cd(II) adsorption isotherms in these soils better. Some previous studies [28,29] also confirmed this, probably because the Langmuir equation neglected the lateral interactions and horizontal mobility of the adsorbed ions [30]. All values of b in this study ranged from 0.605 to 0.765 after 24-h and 120-h adsorption periods. Parameter *b* is a dimensionless parameter commonly less than 1 [31], and also a measure of the heterogeneity extent in sorption sites in equilibrium batch experiments and represents different affinities for Cd(II) by matrix surface. Specifically, the *b* values of these irrigated soils decreased from the initial 24-h sorption period to the finial 120 h sorption, meaning that the heterogeneity extent in sorption sites of soils was altered after a longer reaction time.

3.2. Desorption

With the increase of desorption time, the amount of Cd(II) desorbed from these soils increased (Fig. 4). The desorption amount of Cd(II) after 120 h was only 0.81–0.18 mg kg^{-1}, and 13.1–19.0 mg kg^{-1} in the soils treated by 5 and 50 mg L^{-1} of the initial Cd(II), respectively (Fig. 4A–E). In most cases, more Cd(II) was desorbed from the soil which sorbed more Cd at the end of sorption procedure. After 120 h of desorption, the desorption of Cd(II) was significantly higher in the soil irrigated by RW than that in the original soil at the
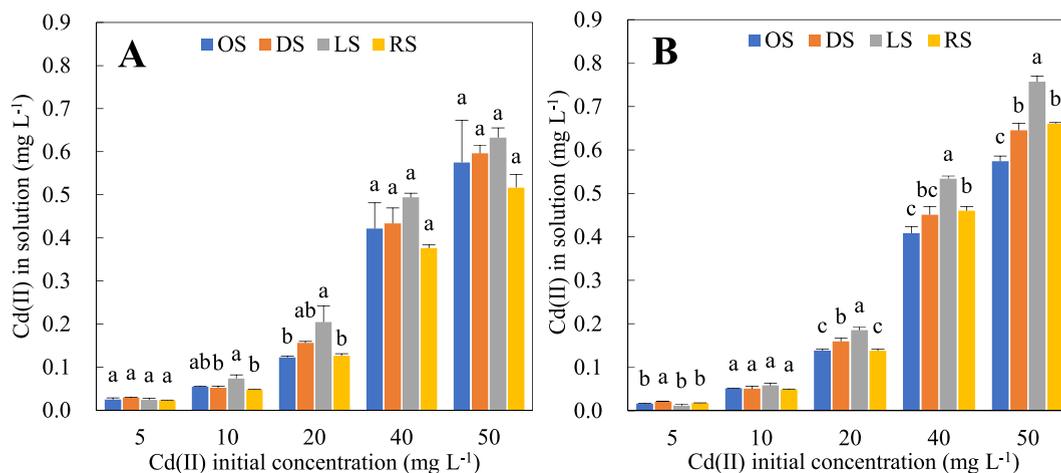
Fig. 2. Cd(II) concentration in the equilibrium solutions of different soils under five Cd(II) initial concentrations within a reaction time of 24 h (A) and 120 h (B), respectively. Error bars represent standard errors, and columns with different letters are significantly different ($p < 0.05$). OS refers to the original soil, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and RS represents the reclaimed water-irrigated soil.
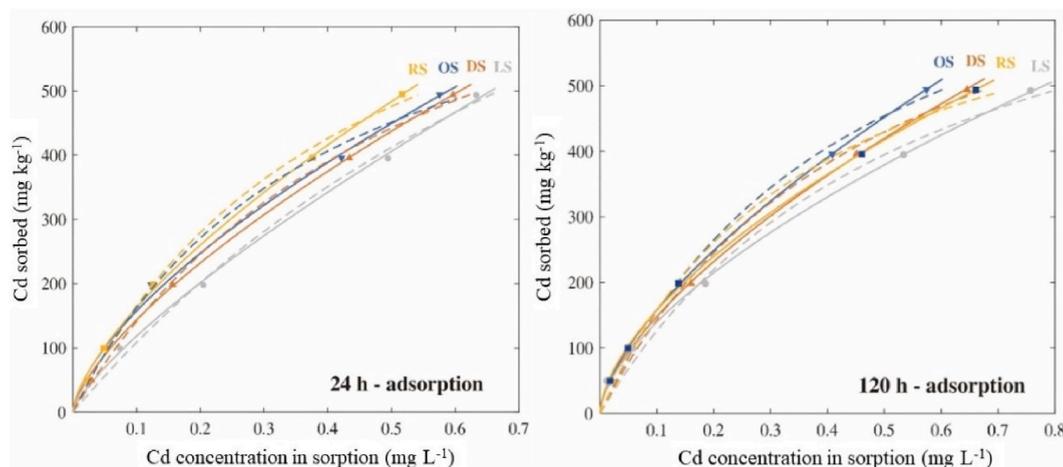
Fig. 3. Adsorption isotherms (scatter plots) and the simulated curves of Cd after 24-h and 120-h of reaction for different soils. Solid and dashed curves presented the simulations by the Freundlich and Langmuir equations, respectively. OS refers to the original soil, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and the reclaimed water-irrigated soil was represented by RS.

Table 1
Freundlich and Langmuir adsorption parameters of cadmium adsorption after 24 and 120 h of reaction for all soils. OS refers to the original soil, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and RS represents the reclaimed water-irrigated soil.

Soil series	Reaction time (h)	Freundlich			Langmuir		
		K_f (L kg^{-1})	b	r^2	S_{max} (mg kg^{-1})	K_d	r^2
OS	24	706.1 ± 86.9	0.651 ± 0.118	0.996	812.3 ± 257.7	2.503 ± 1.606	0.995
	120	710.0 ± 16.2	0.652 ± 0.022	1.000	866.8 ± 330.4	2.199 ± 1.603	0.994
DS	24	706.0 ± 50.4	0.691 ± 0.073	0.999	947.0 ± 398.1	1.753 ± 1.311	0.995
	120	657.8 ± 22.8	0.648 ± 0.037	1.000	862.3 ± 354.2	1.984 ± 1.564	0.994
LS	24	690.4 ± 59.5	0.765 ± 0.103	0.998	1365.0 ± 1312.4	0.865 ± 1.199	0.992
	120	583.2 ± 34.2	0.621 ± 0.071	0.999	843.9 ± 486.3	1.757 ± 1.982	0.987
RS	24	773.0 ± 56.7	0.677 ± 0.066	0.999	896.0 ± 297.4	2.267 ± 1.399	0.996
	120	634.8 ± 26.5	0.605 ± 0.043	0.999	754.8 ± 241.3	2.640 ± 1.846	0.993

initial sorption concentration of 20 mg L^{-1} (Fig. 4C); no significant difference of Cd desorption was observed between the soil irrigated with LW and the original soil; Cd(II) desorption was significantly lower in the soil irrigated by DW than the original soil at 50 mg L^{-1} of initial sorption Cd(II) (Fig. 4E); the desorption of Cd(II) was significantly higher in the soil irrigated with RW than that in the soils irrigated with LW and DW at the initial Cd sorption concentration of 10, 20 and 50 mg L^{-1} (Fig. 4A, C and 4E). There was no significant difference between the treatments irrigated with LW and DW irrespective of the initial Cd(II) sorption concentrations at the end of the five round of desorption.

The change in desorption ratio with time (Fig. 5) was similar to that of desorption amount. The total desorption ratio of Cd(II) in these soils was 0.14%–0.50% at 24 h and 1.62%–3.86% at 120 h (Fig. 5A and E), indicating that most of the adsorbed Cd(II) was firmly immobilized by these soils, and that the desorption did not reach the equilibrium even at 120 h. At 5 mg L^{-1} of initial Cd(II), the desorption ratio of Cd(II) in the soil irrigated with DW was the highest followed by that in the soil irrigated with LW (Fig. 5A). At 10–50 mg L^{-1} of initial Cd(II), the desorption ratio of Cd(II) in the soil irrigated with RW was the highest (Fig. 5B–E). The desorption ratio of Cd(II) in the soil irrigated with LW was evidently lower than that in original soil at 10 and 50 mg L^{-1} of initial Cd(II) (Fig. 5B and E).

3.3. The associations of adsorbed Cd(II) by soil with soil properties

The associations between the adsorbed Cd(II) by soil and the soil properties were presented in Table 2. When the initial Cd(II) concentrations were 40 and 50 mg L^{-1} at the beginning of the adsorption, the Cd adsorption amount was significantly positively associated with the soil pH, and negatively with available P and water soluble Ca^{2+}. At the initial Cd(II) of 20 mg L^{-1}, water soluble Ca^{2+} was notably negatively with the adsorbed Cd(II) by soil. At the initial Cd(II) of 10 mg L^{-1}, carbonate and available Cu showed the significant negative correlations with the soil-sorbed Cd.

4. Discussion

This study compared the Cd adsorption and desorption carried out in a batch experiment between bulk soils collected from a
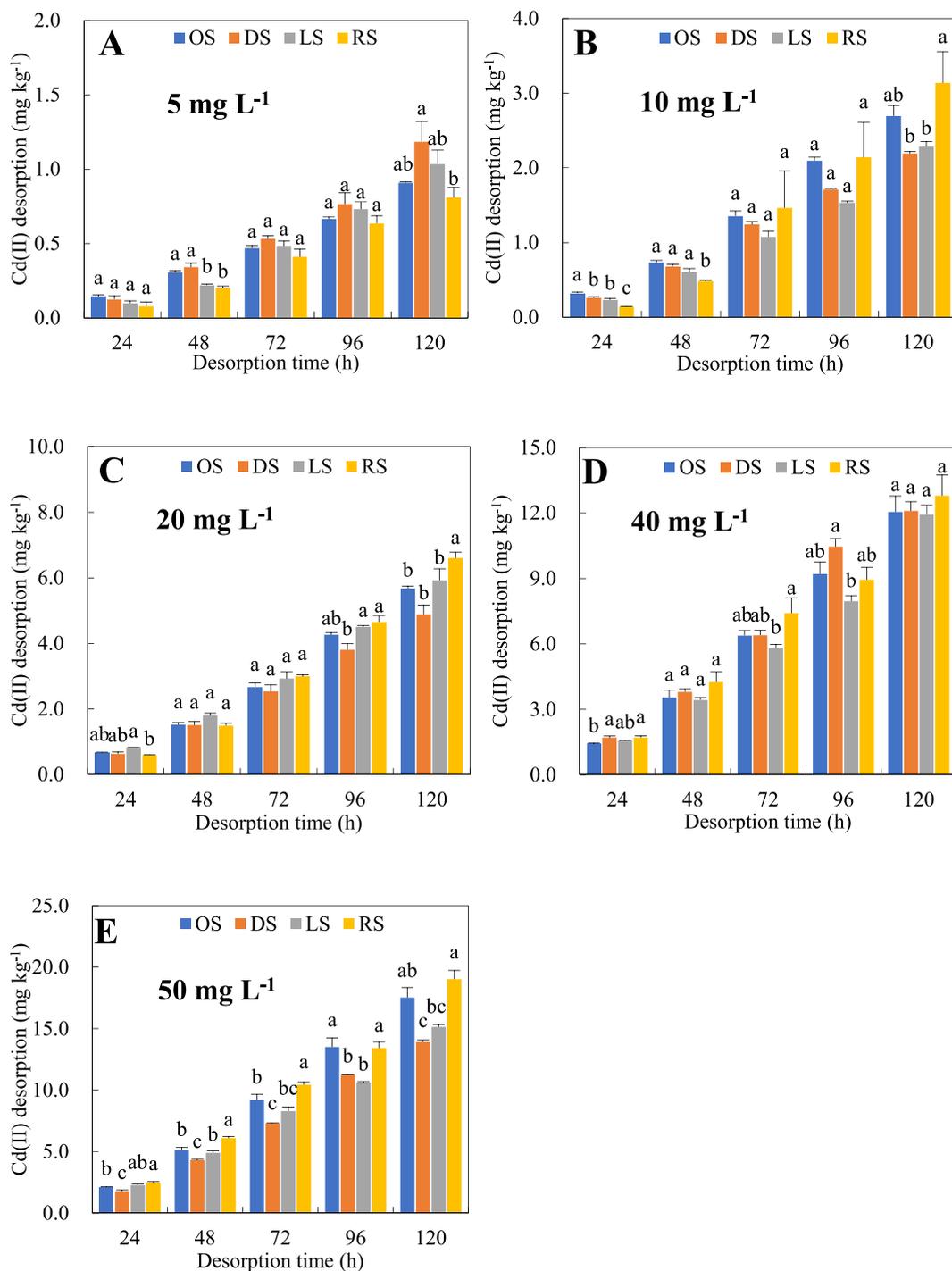
Fig. 4. Desorption of Cd(II) in the soils after 120-h adsorption. A, B, C, D and E refer to the initial sorption Cd(II) concentrations of 5, 10, 20, 40 and 50 mg L^{-1}, respectively. Error bars represent standard errors, and columns with different letters are significantly different ($p < 0.05$). OS refers to the original soil, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and the reclaimed water-irrigated soil was represented by RS.

rhizobox experiment pre-irrigated with RW, LW and DW and the original unirrigated soils at a range of initial Cd sorption concentrations. As we hypothesized, Cd fixation ability of soil was altered by the irrigations. The soils used in this study were potent to fix the Cd in solution. The sorption of Cd(II) by these soils was time- and concentration-dependent. The study with batch sorption-desorption experiments also found that the potential of soils to retain Cd were highly dependent on soil properties as well as the initial Cd
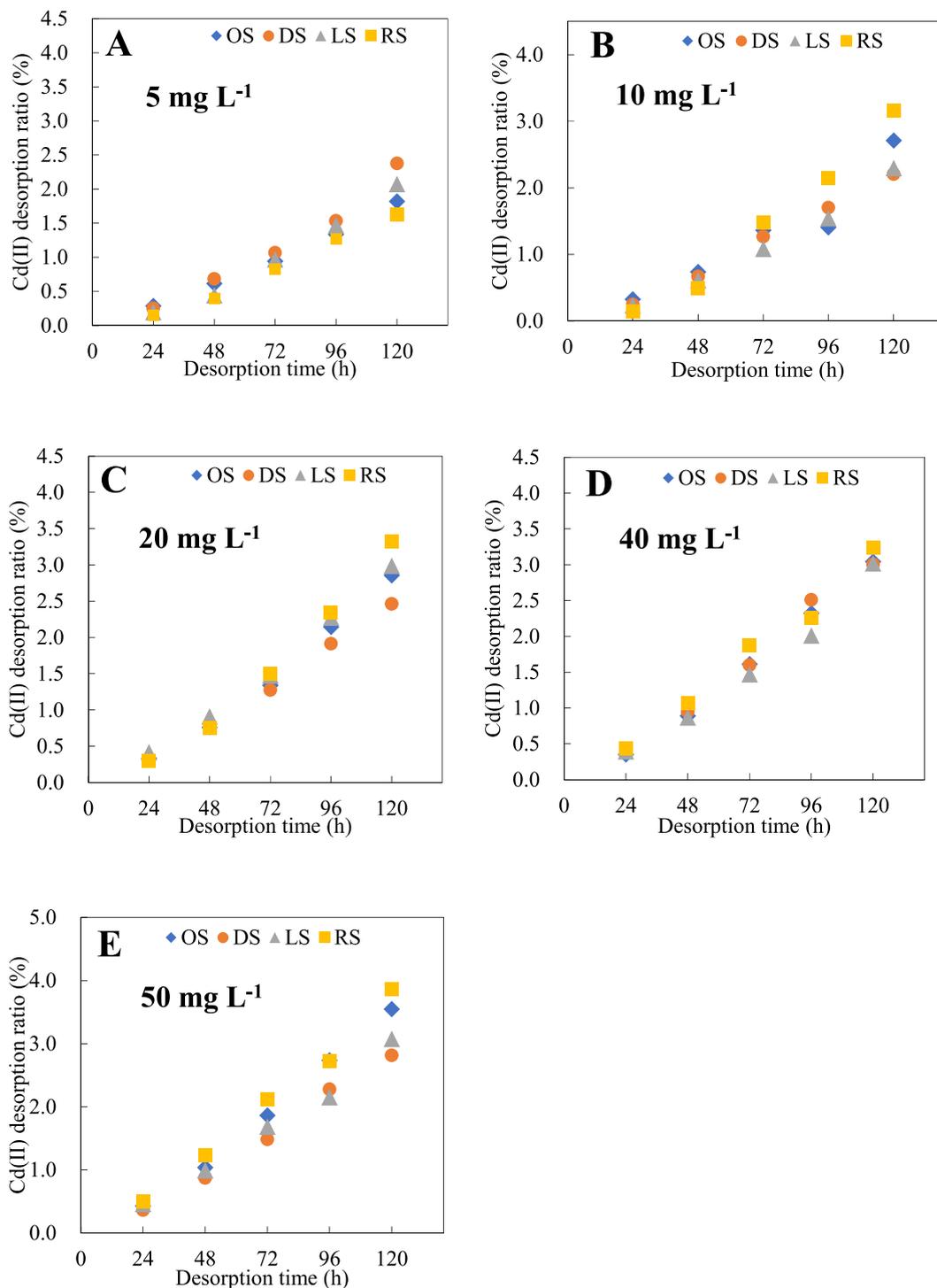
Fig. 5. Desorption ratio of Cd(II) in the previously Cd(II)-sorbed soils with five initial Cd(II) concentrations. A, B, C, D and E represents the initial Cd (II) concentrations of 5, 10, 20, 40 and 50 mg L^{-1}, respectively. OS refers to the original soil, DS refers to the deionized water-irrigated soil, LS refers to the livestock wastewater-irrigated soil and RS refers to the reclaimed water-irrigated soil.

concentration [19]. For the high-initial Cd(II) systems after 120-h sorption, the fertilized and deionized water-irrigated soils showed decreased capability of immobilizing Cd compared with the original soil, and the soils irrigated with livestock wastewater possessed the lowest Cd fixation capability. After 120 h of desorption, reclaimed water-irrigated soils desorbed more Cd than other treatments when the initial Cd was more than 5 mg L^{-1}.

Table 2

Pearson correlation coefficients presenting the correlations between soil-adsorbed Cd(II) after reaction for 120 h and soil physicochemical characteristics.

Items	Initial Cd(II) concentration (mg L^{-1})				
	5	10	20	40	50
pH	−0.407	0.699	0.936	0.992[f]	0.978[e]
EC[a]	0.156	−0.079	−0.366	−0.692	−0.718
OM[b]	0.832	−0.950	−0.884	−0.872	−0.887
ECEC[c]	−0.850	0.374	−0.019	0.117	0.200
Sand	−0.004	−0.167	−0.572	−0.795	−0.786
Silt	0.278	−0.090	0.382	0.608	0.589
Clay	−0.884	0.721	0.272	0.140	0.180
Total N	0.684	−0.389	0.130	0.258	0.210
Total P	0.413	−0.276	−0.449	−0.759	−0.799
Available N	0.652	−0.418	0.094	0.264	0.225
Available P	0.358	−0.525	−0.795	−0.962[e]	−0.964[e]
Available K	0.219	−0.326	−0.646	−0.878	−0.883
ws[d] Na$^+$	−0.040	0.543	0.526	0.158	0.092
ws Ca^{2+}	0.567	−0.750	−0.906	−0.996[f]	−1.000[f]
ws Mg^{2+}	0.447	−0.286	−0.434	−0.746	−0.790
ws K$^+$	−0.038	0.426	0.284	−0.109	−0.165
ws Cl$^-$	0.691	−0.907	−0.956[e]	−0.950	−0.949
ws NO$_3^-$	0.175	−0.135	−0.430	−0.739	−0.762
ws PO$_4^{3-}$	−0.128	0.336	0.048	−0.327	−0.360
ws SO$_4^{2-}$	−0.082	0.299	0.683	0.869	0.857
ws HCO$_3^-$	0.071	−0.498	−0.867	−0.888	−0.846
Carbonate	0.910	−0.979[e]	−0.764	−0.672	−0.690
Available Cu	0.843	−0.950[e]	−0.875	−0.864	−0.879
Available Zn	−0.136	0.213	0.557	0.815	0.822
Available Fe	0.002	0.047	0.423	0.709	0.716
Available Mn	−0.248	−0.118	−0.598	−0.709	−0.667
Available Cd	0.038	0.156	0.575	0.787	0.775

[a] EC-electrical conductivity.
[b] OM-organic matter.
[c] ECEC-effective cation exchange capacity.
[d] ws-water soluble.
[e] Correlation is significant at the 0.05 level.
[f] Correlation is significant at the 0.01 level.

4.1. Response of Cd(II) sorption and desorption to soil properties change due to irrigation

Irrigation undoubtedly led to an alteration of soil physical and chemical properties, thereby controlling Cd(II) mobility and retention in soils [32]. The soil characteristics control Cd sorption via the mutual effects of pH, the combination of precipitation with other anions in soil solution, and the complexion with organic matter, among others [18,29]. In this study, soil pH was positively correlated with the Cd(II) sorption amount (Table 2). Batch sorption experiment also showed that Cd sorption capacity of soils is highly related to soil physicochemical properties, especially controlled by soil pH [33]. The pH influences the ionic state of Cd and the adsorbent functional groups, as well as the surface charge of adsorbent. When the pH is less than 8 (e.g. soil irrigated with LW), free Cd^{2+} cations are the main species in the aqueous solutions; while when the pH value is between 8 and 8.3 (the original soil and soil irrigated with RW and DW), Cd(OH)$^+$ and Cd(OH)$_2$ were the coexisting forms of Cd(II) in addition to the main Cd^{2+} form [34]. Therefore, the precipitation of Cd(OH)$_2$ was higher in RS than LS. Moreover, it is well-known that the adsorption quantity of Cd(II) increases with the increasing initial pH of solution due to the decreased competition by H$^+$ and the increased negative charge on soil surface [35]. OM was also an important factor affecting behavior of metals. Soil OM exhibits high cation exchange capacity (CEC) values and abundant functional groups, thus providing more adsorption sites and facilitating Cd(II) adsorption [23]. While it is also reported that dissolved OM could form ligand-like complexes and reduce Cd(II) adsorption [36], which could partly explain that soil irrigated with dissolved OM-enriched livestock wastewater, adsorbed less Cd(II) in our study. Besides, soil texture is also important influence factor to retain Cd with different fraction [37], possibly more sand and silt in LW-irrigated soil resulted in the less soil surface area, thereby providing fewer adsorption sites for Cd(II) compared with RW- and DW-irrigated soil.

The cations in the soil play an essential role in Cd(II) adsorption and desorption, and the increase in cation content is adverse to the sorption of heavy metals [38]. The Cd sorption and retention in soils highly depend on the competition with other heavy metals for the sorption sites. Ca^{2+}, Mg^{2+}, Cu^{2+}, and Zn^{2+} can be introduced into soils with previous fertilizers and later irrigation with these treated wastewaters, and thus occupied the sorption sites or formed the complexation with other anions to prevent the Cd sorption in soils [35]. The total content of water soluble K$^+$, Na$^+$, Ca^{2+}, Mg^{2+} was higher in LW-irrigated soil (617.7 mg kg^{-1}) than RW-irrigated soil (557.0 mg kg^{-1}) and DW-irrigated soil (413.1 mg kg^{-1}), hence the Cd sorption amount was lower in LW-irrigated soil. In the similar way, the bioavailable Cu and Zn were negatively related with Cd adsorption amount (Table 2) because their higher content in LW-irrigated soil promoted the competitive sorption of these metal cations with Cd, which is consistent with previous studies [39–41].

The promoting effect of water soluble Na^+ and Mg^+ on the release of Cd(II) by the soils after adsorption was also observed (Table S3). The anions are also nonnegligible factors controlling Cd(II) adsorption and desorption. For example, NO_3^-, SO_4^{2-}, and Cl^- could form mononuclear or polynuclear complexes with metal ions in solution and these complexes may carry a positive, negative or zero (neutral) charge depending on the charge and the number of anions involved, which consequently affecting Cd(II) adsorption [42]. It was found that Cl^- would form with Cd compounds whereas NO_3^- and SO_4^{2-} have difficulty forming the complexes with Cd^{2+} in batch adsorption experiment [43,44]. In our study, the NO_3^- content was higher in LW-irrigated soil than other soils, and total content of Cl^- and SO_4^{2-} was higher in RW-irrigated soil. The effect of Cl^- and SO_4^{2-} anions on Cd(II) adsorption was higher than NO_3^-, and Cl^- was proved to form more specific sorption on the soil surface relative to NO_3^- and to occupy more ionic exchange sites [23]. The complexation of Cl^- and SO_4^{2-} with Cd(II) during the desorption stage enhanced the Cd release, which may explain the positive associations between the desorbed Cd and these two anions (Table S3) and the higher desorption of Cd in LW-irrigated soil. The content of PO_4^{3-} and HCO_3^-, which could form precipitates and complexation with Cd(II) [45], were higher in RW-irrigated soil than LW-irrigated soil, thereby contributing to more immobilization of Cd in RW-irrigated soil. Therefore, Cd sorption in soils is complex and can be affected by the type of anions present in the soils, further deciphering the effects of anions on Cd sorption in soils is important to elucidate the mechanisms involved in the Cd migration under treated wastewater irrigation.

What's more, the emerging contaminate antibiotics were always found with higher concentration in livestock wastewater (Table S1) and the corresponding irrigated soils [46], and our soils were no exception. The positively charged groups of antibiotics could compete with Cd(II) for adsorption sites [47], simultaneously the negatively charged groups of antibiotics could form complexes with Cd(II) and be in favor of the mobility of Cd(II). In addition, the antibiotics and metals could be adsorbed on the soil surface by antibiotics-Cd-soil bridging [48,49]. If the ternary complex is more stable than the dissolved Cd-antibiotics complex, the sorption of metals will be enhanced [25]. Therefore, the effect of antibiotics on Cd(II) adsorption is the combination of above processes, and in our study perhaps the antibiotics competition in LW-irrigated soil and the enhanced mobility of Cd-antibiotics complexes were the more powerful processes which inhibited the adsorption of Cd(II) by LW-irrigated soil relative to RW-irrigated soil.

4.2. Response of Cd(II) adsorption by soils to contact time

Cd sorption in soils was found to establish rapid equilibrium followed by a pseudo-second order reaction, the contact time between Cd and soils has a great effect on Cd desorption period [50,51] Adsorption of Cd(II) was a complex process, including a quick reaction in which Cd(II) adsorbed onto the exterior surface of soil colloids and a slow reaction that Cd(II) moved to the interior surface [52], which is also observed from the pH dynamic in this study (Fig. 1). The first quick and the following slow pH change indicated Cd(II) adsorption was mainly driven by chemical adsorption. At the initial stage of adsorption, soil surface provided more adsorption sites, which contributed to the rapidly increased adsorption rate. The negative-charged soil surface could combine with metal cations through Coulomb force, and this process could be considered as non-specific adsorption. Thus, the adsorbed Cd(II) could be easily desorbed from the soil surface by external disturbance in this process. Then, the slow specific adsorption happened through complexation between Cd(II) and soil surface, and it would increase the positive-charged sites of soil surface, which would in turn prevent adsorption of Cd(II), hence it was observed that the Cd(II) concentration increased (Fig. S1) and pH decreased (Fig. 1) in the solution at 120 h compared to that at 24 h. Additionally, when the adsorption amount was increasing, the decreased Cd(II) concentration in solution and available sorption sites on soil surface became limiting factors for Cd(II) adsorption [53].

4.3. Response of Cd(II) adsorption by soils to initial Cd concentration

The concentration of Cd in soil solution is a critical factor that affects the Cd adsorption in soils. The primary and dominant mechanism of interaction between soil particles and Cd is sorption, which means that Cd can be adsorbed onto the soil surface by electrostatic forces. However, at high concentrations of Cd in soil solution, the Cd sorption capacity may become saturated with the form of solution precipitation and soil particle surface [54]. At low concentration (5 mg L^{-1}) of initial Cd(II) in this study, almost all the Cd in the solution could be adsorbed by these soils, therefore a rather small amount of Cd was left in the solution, and no remarkable distinction in the residual Cd occurred between these soils. In other words, when the soil like the one in our study was subjected to the rainwater or the stormwater containing low-level Cd resulted from the heavy air pollution or flood invasion, the adsorption sites on the soil surface were adequate for fixing almost all the enthetic Cd, hence the risk of remaining Cd was low for the soil. At higher concentration (10, 20, 40 and 50 mg L^{-1}) of initial Cd(II), the adsorption sites of soil didn't seem enough to immobilize all the solution Cd. With the increase of the initial Cd concentration, the Cd left in the equilibrium solution increased and varies with different soils. Although the risk increased with high-level of exogenous Cd, the hazard of Cd in soil irrigated with RW was lower compared with that with LW. It is reported that chemisorption (cation exchange) and co-precipitation were the dominate mechanisms at low and high initial Cd(II) loadings respectively [55]. Consequently, the different mechanisms of Cd(II) sorption at low and high Cd loadings might contribute to the discrepancy of the order of Cd(II) adsorption amount among these soils. Another possibility is that the stability field of the Cd species depending on Cd(II) concentrations altered the affinity of different Cd species in these irrigated soils [54].

4.4. Possible reason for the low desorption rate

Sodium nitrate was commonly used to desorb the exchangeable fraction of metals in previous studies [24,25]. Soil exhibits various affinities to retain Cd as indicated by its reaction rates during sorption processes, which is similar to the desorption rate for Cd release. The desorption ratio is rather low in our study, and the desorption amount kept increasing during the 120-h desorption, suggesting that

the release of Cd was a slow process without reaching the equilibrium even after 120 h of desorption, and that a large amount was retained in the soil phase. In this experiment, the exchangeable fraction with high availability only accounted for a small proportion compared to the less mobile complexed fraction, which may explain why the amount of Cd(II) desorption by 0.01 mol L^{-1} NaNO$_3$ was very insignificant in our study. The carbonates and other soil fraction including Fe/Mn oxide might also strongly bound Cd [19,56] and the bounded Cd was very difficult to be desorbed by NaNO$_3$. Distinguishing the different forms (exchangeable fraction, carbonate-bound fraction, easily reducible Mn and Fe oxide fraction, organic bound fraction and residual fraction) of Cd adsorbed on the soil by successive extractions using a series of desorbents may shed more light on the mechanism of Cd adsorption. Overall, the soil used in this study possessed a strong adsorption capacity for Cd, and we guess that the influence of soil property differences on its adsorption capacity is far greater than that of irrigation, which needs further evaluation.

4.5. Applications

Given that more Cd was left in LS solution in adsorption stage at high-initial Cd scenarios, the risk of LW irrigation was higher compared to other treatments, the residual Cd (0.01–0.76 mg L^{-1}) might risk plant growth according to the concentrations of cadmium toxic to plants (Table S4). In desorption stage, reclaimed water irrigation made soil desorb more Cd than other irrigated soils, and the desorption continued even after 120 h, indicating that the desorption of Cd in these soils would possibly cause more serious phyto-toxicity and deserves more concern. For the clean water-irrigated soil, reclaimed water or livestock wastewater irrigation reduce the Cd retention by soil, which is unexpected by us. For the Cd-polluted soil, the Cd mobility may also be enhanced after irrigation with unconventional water sources which needs to be clarified in future studies.

5. Conclusions

The effect of reclaimed water and livestock wastewater irrigation on soil ability in Cd(II) sorption at different initial Cd(II) concentrations with the controls of deionized water irrigation and the original soil before irrigation was investigated via a rhizobox experiment followed by a batch experiment. Reclaimed water and livestock wastewater irrigation notably influenced soil physico-chemical properties, resulting in a different sorption ability of Cd(II) in the associated irrigated soils. With respect to the low initial concentration (5 mg L^{-1}), there were no remarkable differences between sorption of Cd(II) in these soils, especially after 24-h adsorption. However, after 120-h reaction, the Cd adsorption amount of these soils varied with each other obviously with the notable adsorption decline in these irrigated soils particularly for livestock wastewater-irrigated soils. Freundlich model fitted the Cd (II) sorption isotherms in these irrigated soils better than Langmuir model and the maximum sorption of Cd(II) of these irrigated soils for 120 h simulated by both models was lower than that for 24 h. Moreover, a small proportion but continuous release of the sorbed Cd (II) was observed in the desorption stage. In conclusion, the risk of pre-livestock wastewater irrigation was higher than pre-reclaimed water irrigation due to the resulting lower fixation ability of Cd(II) of the irrigated soil, and the incessant release of Cd from soil needs more concern. This study suggests that the risk of livestock wastewater irrigation was higher compared to reclaimed water regarding the Cd migration, and the long-term monitoring of Cd release is also essential for the alkaline sandy soil irrespective of the irrigation waters. It needs to be emphasized that the results could be varied when these tests are carried out in the contaminated soils in the field.

Author contribution statement

Zhongyang Li: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Yuan Liu: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Baogui Li: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Zhen Tao: Performed the experiments; Analyzed and interpreted the data.
Zhijuan Zhao; Tao Fan: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supp. Material/referenced in article.

Additional information

Supplementary Materials: Table S1: Basic properties of reclaimed water and livestock wastewater; Table S2: Properties of original soil (OS), deionized water-irrigated soil (DS), livestock wastewater-irrigated soil (LS) and reclaimed water-irrigated soil (RS) used in this study; Table S3: Pearson correlation coefficients presenting the correlations between soil-desorbed Cd(II) after reaction for 120 h and soil physicochemical characteristics; Table S4: Summary of cadmium concentration range which can cause phytotoxicity; Figure S1: Adsorption isotherms of Cd on different treated soils within a reaction time of 24 h and 120 h, respectively.

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

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e16304.

References

[1] M.V. Rechberger, S. Kloss, S.-L. Wang, J. Lehmann, H. Rennhofer, F. Ottner, et al., Enhanced Cu and Cd sorption after soil aging of woodchip-derived biochar: what were the driving factors? Chemosphere (2019) 216463–216471, https://doi.org/10.1016/j.chemosphere.2018.10.094.

[2] N.H. Afef, G. Houda, C.H. Chiraz, Response of Arabidopsis thaliana, seedlings to cadmium in relation to ammonium availability, Bull. Environ. Contam. Toxicol. 89 (6) (2012) 1175–1180, https://doi.org/10.1007/s00128-012-0840-3.

[3] Y. Yang, C. Xiao, F. Wang, L. Peng, Q. Zeng, S. Luo, Assessment of the potential for phytoremediation of cadmium polluted soils by various crop rotation patterns based on the annual input and output fluxes, J. Hazard Mater. 423 (2022) 127183, https://doi.org/10.1016/j.jhazmat.2021.127183.

[4] H. Li, H. Zhang, Y. Yang, G. Fu, L. Tao, J. Xiong, Effects and oxygen-regulated mechanisms of water management on cadmium (Cd) accumulation in rice (*Oryza sativa*), Sci. Total Environ. 846 (2022) 157484, https://doi.org/10.1016/j.scitotenv.2022.157484.

[5] M. Chen, D. Wang, X. Xu, Y. Zhang, X. Gui, B. Song, N. Xu, Biochar nanoparticles with different pyrolysis temperatures mediate cadmium transport in water-saturated soils: effects of ionic strength and humic acid, Sci. Total Environ. 806 (2022) 150668, https://doi.org/10.1016/j.scitotenv.2021.150668.

[6] S. Feng, P. Zhang, Y. Hu, F. Jin, Y. Liu, S. Cai, et al., Combined application of biochar and nano-zeolite enhanced cadmium immobilization and promote the growth of Pak Choi in cadmium contaminated soil, NanoImpact 28 (2022) 100421, https://doi.org/10.1016/j.impact.2022.100421.

[7] Z. Yang, H. Gong, F. He, E. Repo, W. Yang, Q. Liao, F. Zhao, Iron-doped hydroxyapatite for the simultaneous remediation of lead-, cadmium- and arsenic-co-contaminated soil, Environ. Pollut. 312 (2022) 119953, https://doi.org/10.1016/j.envpol.2022.119953.

[8] K. Zhang, Y. Yi, Z. Fang, Remediation of cadmium or arsenic contaminated water and soil by modified biochar: a review, Chemosphere 311 (2023) 136914, https://doi.org/10.1016/j.chemosphere.2022.136914.

[9] X. Li, J. Zhou, T. Zhou, Z. Li, P. Hu, Y. Luo, et al., Potential mobilization of cadmium and zinc in soils spiked with smithsonite and sphalerite under different water management regimes, J. Environ. Manag. 324 (2022) 116336, https://doi.org/10.1016/j.jenvman.2022.116336.

[10] L. Tang, Y. Hamid, A. Zehra, Z.A. Sahito, Z. He, M.B. Khan, et al., Mechanisms of water regime effects on uptake of cadmium and nitrate by two ecotypes of water spinach (*Ipomoea aquatica* Forsk.) in contaminated soil, Chemosphere 246 (2020) 125798, https://doi.org/10.1016/j.chemosphere.2019.125798.

[11] E. Wen, X. Yang, H. Chen, S.M. Shaheen, B. Sarkar, S. Xu, et al., Iron-modified biochar and water management regime-induced changes in plant growth, enzyme activities, and phytoavailability of arsenic, cadmium and lead in a paddy soil, J. Hazard Mater. 407 (2021) 124344, https://doi.org/10.1016/j.jhazmat.2020.124344.

[12] A. Waleeittikul, S. Chotpantarat, S.K. Ong, Impacts of salinity level and flood irrigation on Cd mobility through a Cd-contaminated soil, Thailand: experimental and modeling techniques, J. Soils Sediments 19 (5) (2019) 2357–2373, https://doi.org/10.1007/s11368-018-2207-9.

[13] M.H. Stietiya, M. Duqqah, T. Udeigwe, R. Zubi, T. Ammari, Fate and distribution of heavy metals in wastewater irrigated calcareous soils, Sci. World J. 2014 (2014) 865934, https://doi.org/10.1155/2014/865934.

[14] X. Li, C. Yang, G. Zeng, S. Wu, Y. Lin, Q. Zhou, et al., Nutrient removal from swine wastewater with growing microalgae at various zinc concentrations, Algal Res. 46 (2020) 101804, https://doi.org/10.1016/j.algal.2020.101804.

[15] F.-M. Zhu, H.-G. Zhu, W.-Y. Shen, T.-H. Chen, Integrating a tidal flow wetland with sweet sorghum for the treatment of swine wastewater and biomass production, Ecol. Eng. (2017) 101145–101154, https://doi.org/10.1016/j.ecoleng.2017.01.021.

[16] Y. Han, L. Yang, X. Chen, Y. Cai, X. Zhang, M. Qian, et al., Removal of veterinary antibiotics from swine wastewater using anaerobic and aerobic biodegradation, Sci. Total Environ. 709 (2020) 136094, https://doi.org/10.1016/j.scitotenv.2019.136094.

[17] D. Zalacáin, S. Martínez-Pérez, R. Bienes, A. García-Díaz, A. Sastre-Merlín, Salt Accumulation in Soils and Plants under Reclaimed Water Irrigation in Urban Parks of Madrid (Spain), Agric. Water Manage. (2019) 213468–213476, https://doi.org/10.1016/j.agwat.2018.10.031.

[18] Z. Tan, S. Yuan, M. Hong, L. Zhang, Q. Huang, Mechanism of negative surface charge formation on biochar and its effect on the fixation of soil Cd, J. Hazard Mater. 384 (2020) 121370, https://doi.org/10.1016/j.jhazmat.2019.121370.

[19] T.A. Elbana, H.M. Selim, Modeling of cadmium and nickel release from different soils, Geoderma (2019) 33878–33887, https://doi.org/10.1016/j.geoderma.2018.11.041.

[20] E.-P. Cui, F. Gao, Y. Liu, X.-Y. Fan, Z.-Y. Li, Z.-J. Du, et al., Amendment soil with biochar to control antibiotic resistance genes under unconventional water resources irrigation: proceed with caution, Environ. Pollut. (2018) 240475–240484, https://doi.org/10.1016/j.envpol.2018.04.143.

[21] IUSS Working Group WRB, World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, fourth ed., International Union of Soil Sciences (IUSS), Vienna, Austria, 2022, p. 234.

[22] T.-T. Fan, Q. Sun, P.-X. Cui, L. Xuan, Y.-J. Wang, Sorption mechanism of cadmium on soils: a combination of batch experiment, path analysis, and EXAFS techniques, Geoderma 422 (2022) 115950, https://doi.org/10.1016/j.geoderma.2022.115950.

[23] B. Ren, Y. Wu, D. Deng, X. Tang, H. Li, Effect of multiple factors on the adsorption of Cd in an alluvial soil from Xiba, China, J. Contam. Hydrol. 232 (2020) 103605, https://doi.org/10.1016/j.jconhyd.2020.103605.

[24] F.A. Vega, M.L. Andrade, E.F. Covelo, Influence of soil properties on the sorption and retention of cadmium, copper and lead, separately and together, by 20 soil horizons: comparison of linear regression and tree regression analyses, J. Hazard Mater. 174 (1) (2010) 522–533, https://doi.org/10.1016/j.jhazmat.2009.09.083.

[25] Y. Zhao, Y. Tan, Y. Guo, X. Gu, X. Wang, Y. Zhang, Interactions of tetracycline with Cd (II), Cu (II) and Pb (II) and their cosorption behavior in soils, Environ. Pollut. (2013) 180206–180213, https://doi.org/10.1016/j.envpol.2013.05.043.

[26] Langmuir and Irving, The adsorption of gases on plane surfaces of glass, mica and platinum, J. Am. Chem. Soc. 40 (9) (1918) 1361–1403, https://doi.org/10.1021/ja02242a004.

[27] G. Sposito, Derivation of the Freundlich equation for ion exchange reactions in soils, Soil Sci. Soc. Am. J. 44 (3) (1980) 652–654, https://doi.org/10.2136/sssaj1980.03615995004400030045x.

[28] Y. Zhou, S. Sherpa, M.B. McBride, Pb and Cd chemisorption by acid mineral soils with variable Mn and organic matter contents, Geoderma 368 (2020) 114274, https://doi.org/10.1016/j.geoderma.2020.114274.

[29] C.D. Tsadilas, D. Dimoyiannis, V. Samaras, Effect of zeolite application and soil pH on cadmium sorption in soils, Commun. Soil Sci. Plant Anal. 28 (17–18) (1997) 1591–1602, https://doi.org/10.1080/00103629709369899.

[30] H.B. Bradl, Adsorption of heavy metal ions on soils and soils constituents, J. Colloid Interface Sci. 277 (1) (2004) 1–18, https://doi.org/10.1016/j.jcis.2004.04.005.

[31] B. Buchter, B. Davidoff, M.C. Amacher, C. Hinz, I.K. Iskandar, H.M. Selim, Correlation of Freundlich Kd and n retention parameters with soils and elements, Soil Sci. 148 (5) (1989) 370–379, https://doi.org/10.1097/00010694-198911000-00008.

[32] M. Wang, S. Chen, L. Chen, D. Wang, C. Zhao, The responses of a soil bacterial community under saline stress are associated with Cd availability in long-term wastewater-irrigated field soil, Chemosphere 236 (2019) 124372, https://doi.org/10.1016/j.chemosphere.2019.124372.

[33] F.-J. Zhao, P. Wang, Arsenic and cadmium accumulation in rice and mitigation strategies, Plant Soil 446 (1–2) (2019) 1–21, https://doi.org/10.1007/s11104-019-04374-6.

[34] Q. Kong, C. Wei, S. Preis, Y. Hu, F. Wang, Facile preparation of nitrogen and sulfur co-doped graphene-based aerogel for simultaneous removal of Cd^{2+} and organic dyes, Environ. Sci. Pollut. Res. 25 (21) (2018) 21164–21175, https://doi.org/10.1007/s11356-018-2195-8.

[35] P. Loganathan, S. Vigneswaran, J. Kandasamy, R. Naidu, Cadmium sorption and desorption in soils: a review, Crit. Rev. Environ. Sci. Technol. 42 (5) (2012) 489–533, https://doi.org/10.1080/10643389.2010.520234.

[36] W. Zhou, L. Ren, L. Zhu, Reducement of cadmium adsorption on clay minerals by the presence of dissolved organic matter from animal manure, Environ. Pollut. (2017) 223247–223254, https://doi.org/10.1016/j.envpol.2017.01.019.

[37] F. Rassaei, M. Hoodaji, S. Ali Abtahi, Cadmium fractions in two calcareous soils affected by incubation time, zinc and moisture regime, Commun. Soil Sci. Plant Anal. 51 (4) (2020) 456–467, https://doi.org/10.1080/00103624.2020.1718685.

[38] T. Suzuki, K. Nakase, T. Tamenishi, M. Niinae, Influence of pH and cations contained in rainwater on leaching of Cd(II) from artificially contaminated montmorillonite, J. Environ. Eng. 8 (5) (2020) 104080, https://doi.org/10.1016/j.jece.2020.104080.

[39] W. Liu, T. Wang, A.G.L. Borthwick, Y. Wang, X. Yin, X. Li, J. Ni, Adsorption of Pb^{2+}, Cd^{2+}, Cu^{2+} and Cr^{3+} onto titanate nanotubes: competition and effect of inorganic ions, Sci. Total Environ. (2013) 456171–456180, https://doi.org/10.1016/j.scitotenv.2013.03.082.

[40] Z. Meng, S. Huang, J. Wu, Z. Lin, Competitive adsorption and immobilization of Cd, Ni, and Cu by biochar in unsaturated soils under single-, binary-, and ternary-metal systems, J. Hazard Mater. 451 (2023) 131106, https://doi.org/10.1016/j.jhazmat.2023.131106.

[41] F. Rassaei, M. Hoodaji, S.A. Abtahi, Adsorption kinetic and cadmium fractions in two calcareous soils affected by zinc and different moisture regimes, Paddy Water Environ. 18 (4) (2020) 595–606, https://doi.org/10.1007/s10333-020-00804-9.

[42] G. Naja, B. Volesky, The mechanism of metal cation and anion biosorption, in: P. Kotrba, M. Mackova, T. Macek (Eds.), Microbial Biosorption of Metals, Springer Netherlands, Dordrecht, 2011, pp. 19–58.

[43] N. Zheng, W. Yue, J. Wu, K. Hou, L. Wu, M. Guo, Y. Teng, Responses of soil cadmium desorption under different saline environments and its controlling factors, Agronomy 11 (11) (2021) 2175, https://doi.org/10.3390/agronomy11112175.

[44] C. Zhang, P.W.G. Sale, C. Tang, Cadmium uptake by Carpobrotus rossii (Haw.) Schwantes under different saline conditions, Environ. Sci. Pollut. Res. 23 (13) (2016) 13480–13488, https://doi.org/10.1007/s11356-016-6508-5.

[45] H. Zhang, J. Shao, S. Zhang, X. Zhang, H. Chen, Effect of phosphorus-modified biochars on immobilization of Cu (II), Cd (II), and As (V) in paddy soil, J. Hazard Mater. 390 (2020) 121349, https://doi.org/10.1016/j.jhazmat.2019.121349.

[46] N. Zhu, H. Jin, X. Ye, W. Liu, D. Li, G.M. Shah, Y. Zhu, Fate and driving factors of antibiotic resistance genes in an integrated swine wastewater treatment system: from wastewater to soil, Sci. Total Environ. 721 (2020) 137654, https://doi.org/10.1016/j.scitotenv.2020.137654.

[47] D. Dong, L. Li, L. Zhang, X. Hua, Z. Guo, Effects of lead, cadmium, chromium, and arsenic on the sorption of lindane and norfloxacin by river biofilms, particles, and sediments, Environ. Sci. Pollut. Res. 25 (5) (2018) 4632–4642, https://doi.org/10.1007/s11356-017-0840-2.

[48] Y. Wan, Y. Bao, Q. Zhou, Simultaneous adsorption and desorption of cadmium and tetracycline on cinnamon soil, Chemosphere 80 (7) (2010) 807–812, https://doi.org/10.1016/j.chemosphere.2010.04.066.

[49] A.A. MacKay, B. Canterbury, Oxytetracycline sorption to organic matter by metal-bridging, J. Environ. Qual. 34 (6) (2005) 1964–1971, https://doi.org/10.2134/jeq2005.0014.

[50] C.W. Gray, R.G. McLaren, A.H.C. Roberts, L.M. Condron, Sorption and desorption of cadmium from some New Zealand soils: effect of pH and contact time, Soil Res. 36 (2) (1998) 199–216, https://doi.org/10.1071/S97085.

[51] T.H. Christensen, Cadmium soil sorption at low concentrations: I. Effect of time, cadmium load, pH, and calcium, Water Air Soil Pollut. 21 (1) (1984) 105–114, https://doi.org/10.1007/BF00163616.

[52] Q.M. Cheng, Q. Huang, S. Khan, Y.J. Liu, Z.N. Liao, G. Li, Y.S. Ok, Adsorption of Cd by peanut husks and peanut husk biochar from aqueous solutions, Ecol. Eng. (2016) 87240–87245, https://doi.org/10.1016/j.ecoleng.2015.11.045.

[53] Y. Huang, C. Fu, Z. Li, F. Fang, W. Ouyang, J. Guo, Effect of dissolved organic matters on adsorption and desorption behavior of heavy metals in a water-level-fluctuation zone of the Three Gorges Reservoir, China, Ecotoxicol. Environ. Saf. 185 (2019) 109695, https://doi.org/10.1016/j.ecoenv.2019.109695.

[54] A. Kubier, R.T. Wilkin, T. Pichler, Cadmium in soils and groundwater: a review, Appl. Geochem. 108 (2019) 104388, https://doi.org/10.1016/j.apgeochem.2019.104388.

[55] I.A.M. Ahmed, N.M.J. Crout, S.D. Young, Kinetics of Cd sorption, desorption and fixation by calcite: a long-term radiotracer study, Geochem. Cosmochim. Acta 72 (6) (2008) 1498–1512, https://doi.org/10.1016/j.gca.2008.01.014.

[56] T. Yang, Y. Xu, Q. Huang, Y. Sun, X. Liang, L. Wang, Removal mechanisms of Cd from water and soil using Fe-Mn oxides modified biochar, Environ. Res. 212 (2022) 113406, https://doi.org/10.1016/j.envres.2022.113406.