COMPARATIVE EFFECTS OF LIME AND BIOCHAR ON ACCUMULATION AND TRANSLOCATION OF CD IN *DICTYOPHORA RUBROVOLVATA* AND THE EVALUATION OF ITS EDIBLE SAFETY

LIU, G. H.[1] – FAN, C. W.[1] – QIN, S.[1] – CHAI, G. Q.[1] – WANG, L.[1] – JIANG, Y.[1] – WANG, H.[2*]

[1]*Institute of Soil and Fertilizer, Guizhou Academy of Agricultural Sciences, Guiyang 550006, China*

[2]*Guizhou Chuyang Ecological Environmental Protection Technology Co., Ltd., Guiyang 550025, China*

**Corresponding author*
e-mail: wanghu011@126.com

(Received 18th Sep 2025; accepted 5th Dec 2025)

Abstract. Edible fungi easily accumulate cadmium (Cd). Lime (LM) and biochar (BC) had a passivation effect on soil Cd. However, there is limited research on Cd passivation and enrichment in *Dictyophora rubrovolvata* (DR). Cultivation experiments were conducted by adding LM and BC. The presence of Cd in the DR system was also examined. The results showed that the applications of LM and BC increased soil pH, with an increase range from 1.54 to 1.97 for LM and from 0.36 to 1.31 for BC. LM and BC decreased DTPA-Cd content in soil, with decreases ranging from 29.26% to 57.95% for LM and from 0.33% to 38.93% for BC. The Cd content in the different parts of DR followed the order thallus > pileus > volva. Soil pH and Cd content in different parts of DR were significantly negatively correlated. DTPA-Cd and Cd content of thallus and volva showed a significant positive correlation. Redundancy analysis revealed a significant correlation between pH, DTPA-Cd in soil, and Cd accumulation in DR. The Cd content of thalli in LM and BC decreased by 6.29%-27.33% and 2.15%-20.47%. The THQ of thallus in LM and BC was also significantly reduced, but THQ of Cd was greater than 1 for adults and children. 3% LM or 5% BC could be employed for Cd-contaminated soil in DR. Compared with BC, LM was more applicable in the remediation of Cd-contaminated soils with DR.
Keywords: *remediation materials, fungi, heavy metals, target hazard quotient, health risk*

Introduction

Heavy metals in soil have become a severe problem worldwide because of rapid industrialization, urbanization, and intensive agriculture. Pb, Cd, Hg, and Cr are examples of potentially toxic elements that are highly deleterious, even at low concentrations (Sharma et al., 2024; Wang et al., 2024). The presence of these elements can cause neurological damage and cancer and may lead to developmental disorders (Yadav et al., 2024). Cd concentration is significantly higher than other toxic and harmful elements in soil (Akkajit and Tongcumpou, 2010; Zhang et al., 2018). Soil Cd pollutants at 7.0% of the points exceeded the standard rate in China (Wang et al., 2023), which is concentrated in Southwest Karst areas. Guizhou Province is the center of the karst region in southwestern China (Sun et al., 2019). A survey of 132,071 cultivated land samples across China revealed that the background value of Cd in Guizhou's soil was 0.659 mg/kg, which was higher than the soil pollution risk screening values of 0.30 mg/kg (pH < 7.5) or 0.60 mg/kg (pH > 7.5) (GB15618-1995, Chinese soil environmental standard) (Zhang et al., 2015). Therefore, Guizhou emerged as a high-risk region for Cd exposure.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

Cd is the primary source of health risks in edible mushrooms (Qin et al., 2024). The concentrations of Cd were higher than the national standard of China (0.2 mg/kg for Cd) (Liu et al., 2015). Many measures have been studied to reduce Cd bioavailability in soil and reduce the absorption of crops. LM and BC are commonly used as heavy metal remediation materials (Feng et al., 2020). LM can effectively reduce the migration and bioavailability of Cd in soil, inhibiting absorption of Cd in rice (Xiao et al., 2017), wheat (Lombi et al., 2002), barley (Oliver et al., 1996), and spinach (Puschenreiter et al., 2005). Cd bioavailability decreased, as noted in a 69% reduction in rice uptake of Cd (Cui et al., 2019). DR belongs to Dictyophora, a subphylum of Basidiomycetes. It has both high nutritional and medicinal value and is known as the “Queen of fungi.” Guizhou Province has become one of the main producers of DR products in China (Chen et al., 2021). Research on heavy metals in mushrooms mainly focused on health risk assessment in edible fungi in the past. Edible fungi can easily accumulate Cd. However, Limited research has been conducted on the resistance of lime and biochar to Cd enrichment in DR.

In this study, Cd-contaminated soil was collected, and different concentrations of lime and biochar were added to conduct DR cultivation experiments. The primary aims of this study were to (1) analyze the content of Cd in soil and DR, (2) explore the accumulation and translocation of Cd in DR, and (3) assess the health risks posed by Cd in DR. The results provide scientific data and theoretical support for the safe production and soil remediation of DR in Cd-contaminated Soil.

Materials and methods

Soil collection and preparation

Soil samples were collected from the surface (0-20 cm) of farmland in Zhijin County, Guizhou Province, China (105°51′42″E and 26°36′15″N), and transported back to laboratory. Soil samples were cleared of large gravel, stones, and branches. The soil sample was sieved through a 2 mm to conduct a DR pot experiment. The physical and chemical properties of the collected soil samples (n = 3) were characterized as follows: pH was 5.88 ± 0.47, the organic matter content was 39.22 ± 0.66 $g \cdot kg^{-1}$, the available nitrogen content was 278.11 ± 37.04 $mg \cdot kg^{-1}$, the available phosphorus content was 20.20 ± 3.39 $mg \cdot kg^{-1}$, the available potassium content was 136.70 ± 38.75 $mg \cdot kg^{-1}$, the total cadmium concentration was 0.87 ± 0.16 $mg \cdot kg^{-1}$, and the DTPA-Cd concentration was 0.186 ± 0.04 $mg \cdot kg^{-1}$.

Design of experiments and samples collection

Each pot ($15^{x}20$ cm) was filled with a mixture of 36.5 kg soil and remediation materials (LM or BC). According to previous research (Butnan et al., 2015; Zhang et al., 2021), LM and BC were added to the soil at 0.5% (LM-1 and BC-1), 1% (LM-2 and BC-2), 3% (LM-3 and BC-3), and 5% (LM-4 and BC-4), respectively. Each treatment was repeated with three replicates. In addition, a control group (CK) was established. After mixing and stabilizing for 1 week, DR was transplanted into each pot. DR was provided by Guizhou Zhijin Siwei Dictyophora Industry Development Co., Ltd., located in Zhijin County, China. LM was procured from a local farmer’s market. LM primarily comprised CaO, with a12.70 pH. BC was obtained from the Zhuqing Carbon Plant in Beishankou County, Gongyi City, Henan Province, China. BC was coconut shell biomass carbon, with a pH of 10.40.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

Soil moisture, temperature, and air Humidity were controlled 55%-60%, 23 ± 2°C, and 60%-70% in a greenhouse, respectively. Soil and DR samples were collected after 120 days. DR was separated into 3 parts (volva (T), thallus (J), and pileus (G)) and dried. The DR sample was sieved through a 0.25 mm mesh to determine concentration of Cd. The soil samples were sieved through 0.15- and 2-mm nylon mesh to determine concentration of pH, total Cd content, and DTPA-Cd.

Analyzing the samples

The pH was measured utilizing the electrode technique with a soil-to-water ratio of 1:2.5 (w/v) (Wang et al., 2023). The total concentration of Cd in soil was determined by digestion with a mixture of HF, HNO_3, and $HClO_4$ (Jiang et al., 2019). The extractable Cd content in the soil was determined by extracting with a solution containing 0.005 $mol·L^{-1}$ DTPA, 0.10 $mol·L^{-1}$ triethanolamine, and 0.01 $mol·L^{-1}$ $CaCl_2$ for 1 h, followed by quantification of the resulting supernatant (Zhang et al., 2017). The determination of Cd content within DR was preceded by digestion with HNO_3-H_2O_2 (Wang et al., 2023). The concentration of Cd within the elution/extraction solution was determined using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS, 7500a, Agilent Technologies, USA).

The linearity, precision, recovery rate, limit of detection (LOD), and limit of quantification (LOQ) of Cd were determined to ensure the accuracy and reliability of the test results (*Table 1*). The Linear equation was $y = 2527.745x + 23.7857$. The correlation coefficient (R) of the standard curve was 0.9999, indicating a good linear relationship within a certain range. The LOD was 0.002 mg/kg and the LOQ was 0.006 mg/kg. The spiked recovery rate of Cd was 92.5–99.0%, with a relative standard deviation of 0-8.0%. Parallel and blank samples were incorporated throughout all analyses to establish rigorous quality control measures and to ensure accuracy. In addition, the national standard materials (HTSB-2 and GSB27) were used, and the relative standard deviations for the parallels were below 15.0%.

Table 1. *The measurement parameters of ICP-MS*

Item	Argument	Item	Argument
Torch horizontal position / mm	0.2	Plasma power / W	1550
Torch vertical position / mm	0.2	Sampling depth / mm	8.0
Atomizing gas compensation / ($L·min^{-1}$)	-0.06	Atomizing gas / ($L·min^{-1}$)	0.99
Discriminator / mV	3.3	Peristaltic pump / rps	0.10
Analog HV / V	2138	Plasma gas / ($L·min^{-1}$)	15.0
HV in the pulse / V	1197	Auxiliary gas / ($L·min^{-1}$)	0.90

Accumulation and translocation of Cd

The bioconcentration factor (BCF) was determined by quantifying the heavy metal content in crops relative to that present in the soil. The translocation factor (TF) represents the ratio of heavy metal content in subsequent plant parts to that in preceding parts. In this study, the BCF and TF were calculated using *Equations 1–5*:

$$BCF_{J/S} = C_{thallus}/C_{soil} \quad \text{(Eq.1)}$$

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

$$BCF_{T/S} = C_{\text{volva}}/C_{\text{soil}} \quad \text{(Eq.2)}$$

$$BCF_{G/S} = C_{\text{pileus}}/C_{\text{soil}} \quad \text{(Eq.3)}$$

$$TF_{J/T} = C_{\text{volva}}/C_{\text{thallus}} \quad \text{(Eq.4)}$$

$$TF_{G/J} = C_{\text{thallus}}/C_{\text{pileus}} \quad \text{(Eq.5)}$$

where C_{thallus}, C_{volva}, C_{pileus}, and C_{soil} are the concentrations of Cd in the thallus, volva, pileus, and soil, respectively. where $BCF_{J/S}$, $BCF_{T/S,}$ and $BCF_{G/S}$ are the accumulation factors of Cd from the soil to the thallus, volva, and pileus, respectively. $TF_{J/T}$ and $TF_{G/J}$ are the translocation factors of Cd from the volva to the thallus and thallus to the pileus, respectively.

Health risk assessment

The target hazard quotient (THQ) can simultaneously evaluate single and multiple heavy metal combined exposures and is a risk assessment method established by the National Environmental Protection Agency of the United States based on the average weight of adults and children (Qin et al., 2024). This method assumes that the absorbed dose of pollutants is equal to the ingested dose, and the ratio of the measured intake dose to the reference dose is used as the evaluation standard. Values less than 1 indicate no significant health risks for the exposed population. There is a health risk. The risk of a single heavy metal is calculated using *Equation 6* (Du et al., 2018; Fu et al., 2020; Peng et al., 2018):

$$THQ = \frac{E_F \times E_D \times F_{IR} \times C}{R_{FD} \times W_{AB} \times T_A} \times 10^{-3} \quad \text{(Eq.6)}$$

where E_F is the exposure frequency, which is 365 days/year. E_D is the exposure range, which is 70 years. F_{IR} is the edible fungus intake rate, children is 115.8 g/person per day, Adults are 150.7 g/person/day. C is the heavy metal content of edible mushrooms (mg kg^{-1}). R_{FD} is the reference dose, where R_{FD} (Cd) = 1×10^{-3} mg (kg·d)$^{-1}$. W_{AB} refers to the average weight of the human body, which is 32.7 kg for children and 55.9 kg for adults. and T_A refers to the average time of exposure, generally 25,550 d.

Statistical analysis

Data were sorted using Microsoft Excel 2016 (Redlands, CA, USA), and the mean ± SD (n = 3) was used to present the data in graphs and tables. The statistical relationships among all data were analyzed using one-way analysis of variance (ANOVA), and the least significant difference (LSD) was used to determine if significant differences existed between the mean values ($P < 0.05$) in SPSS (version 20.0. IBM, Inc., Armonk, NY, USA). Correlation analyses and plotting were conducted using Origin 2021Pro software (Origin Lab, Northampton, MA, USA). Canoco5 was employed for redundancy analysis (RDA) to test the significance of explanatory variables over response variables.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

Results

pH, total Cd, and DTPA-Cd concentrations in soils

The pH and DTPA-Cd concentrations in soil are shown in *Figure 1*. Compared to CK, LM and BC treatments exhibited significant increases in soil pH of 26.27%-33.48% and 6.19%-22.38%, respectively. The LM treatment resulted in higher pH levels than the BC treatment. Compared with BC, the pH of LM-1, LM-2, LM-3, and LM-4 increased by 18.90%, 17.84%, 8.36%, and 9.07%, respectively (*Fig. 1a*). Compared with CK, LM treatments significantly reduced DTPA-Cd content by 29.26%, 43.21%, 49.94%, and 57.95% ($p < 0.05$) (*Fig. 1b*). Compared to CK, the DTPA-Cd content in the BC-3 and BC-4 treatments was significantly reduced by 24.91% and 38.93% ($p < 0.05$), respectively. In contrast, the BC-1 and BC-2 treatments failed to exert a significant influence on this parameter. The DTPA-Cd concentrations observed in the LM treatments were consistently lower than those found in the BC treatment. Furthermore, the reductions in DTPA-Cd content for LM-1, LM-2, LM-3, and LM-4 were 29.02%, 40.33%, 33.33%, and 31. l5%, respectively. The Cd content ranged from 0.65-0.73 $mg \cdot kg^{-1}$ (*Table 2*). No significant difference was observed in the total Cd content among the treatment groups. This indicates that the application of LM and BC exerted an influence on DTPA-Cd content rather than total Cd content. Thus, the application of LM and BC primarily regulates the transformation of Cd forms.

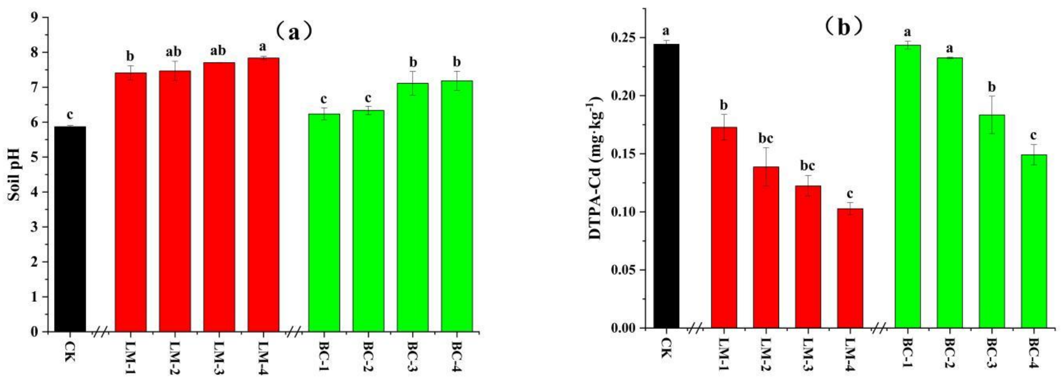

Figure 1. *Effect of different concentrations of conditioners on soil pH (a) and DTPA-Cd (b) (Distinct lowercase letters at the top of the histogram indicate statistically significant differences among various treatments using the same conditioner (p < 0.05). The same is true for the lower section)*

Table 2. *Total Cd concentrations in soils*

Treatment		Total Cd
CK		0.66 ± 0.05a
LM	LM-1	0.68 ± 0.06a
	LM-2	0.73 ± 0.05a
	LM-3	0.71 ± 0.03a
	LM-4	0.67 ± 0.04a
BC	BC-1	0.72 ± 0.04a
	BC-2	0.65 ± 0.05a
	BC-3	0.70 ± 0.06a
	BC-4	0.73 ± 0.07a

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

The Cd content in different parts of DR

The implementation of LM and BC led to a significant reduction in Cd content across various components of DR. The thallus (J) exhibited the highest concentration, followed by the pileus (G) and volva (T). Compared to CK, LM treatment reduced Cd content by 6.29%-24.08%, 15.54%-26.27%, and 9.86%-24.72% in J, G, and T, respectively (*Fig. 2a*). Compared to CK, LM-3 and LM-4 significantly reduced Cd content in thallus. Compared to CK, LM and BC treatments exhibited a significant decrease in Cd content of G. LM-4 treatment demonstrated a significant reduction in Cd content of T ($p < 0.05$). Similarly, BC treatment also led to a decrease in Cd content ranging from 2.16%-20.47%, 11.01%-29.05%, and 2.26%-22.88% in J, G, and T, respectively, compared to CK (*Fig. 2b*). The Cd content of J, G, and T exhibited a significant decrease compared that with of CK for the BC-3 and BC-4 treatments. The application of LM (3% and 5%) generally exhibited a more pronounced effect on the reduction of Cd accumulation than BC. LM and BC exhibited significantly lower levels of Cd accumulation than CK.

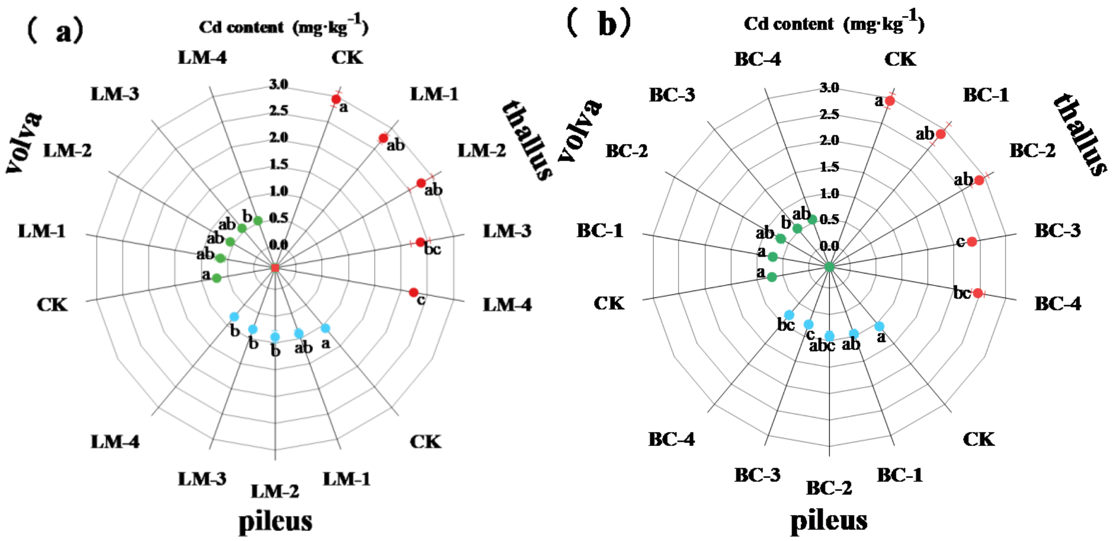

Figure 2. *The impact of LM (a) and BC (b) on the concentration of Cd in different parts of DR*

Accumulation and translocation of heavy metals in DR

The application of LM and BC led to a reduction in the BCFs of Cd in the DR, with $BCF_{J/S} > BCF_{G/S} > BCF_{T/S}$ (*Table 3*). Furthermore, the application of LM and BC resulted in a significant reduction in BCFs of Cd in different parts of DR. Compared to CK, LM treatment decreased the BCFs of $BCF_{J/S}$, $BCF_{G/S}$, and $BCF_{T/S}$ by 9.38%-25.45%, 18.40%-29.45%, and 12.96%-27.78% respectively. LM-2, LM-3, and LM-4 treatments significantly reduced $BCF_{J/S}$, $BCF_{G/S}$, and $BCF_{T/S}$ ($p < 0.05$). For BC treatment, BCFs of Cd in different parts of DR were reduced by 0.89%-25.67%, 13.50%-33.74%, and 4.63%-27.78% respectively. Compared with CK, BC-3 and BC-4 significantly decreased $BCF_{J/S}$, $BCF_{G/S}$, and $BCF_{T/S}$ ($p < 0.05$), and BC-2 to BC-4 also significantly reduced $BCF_{G/S}$ ($p < 0.05$). The BCF of Cd in the DR was greater than 3 under LM and BC.

$TF_{J/T}$ and $TF_{G/J}$ are shown in *Table 4* under LM and BC. $TF_{J/sT}$ exhibited a significantly greater value than $TF_{G/J}$, thereby suggesting the predominant transportation

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

and accumulation of soil Cd within DR's thallus region of DR. No notable disparity between $TF_{J/T}$ and $TF_{G/J}$ was observed upon increasing the soil conditioner concentration, henceforth indicating an insignificant influence on organ-specific translocation factors due to LM and BC addition.

Table 3. *Presents the BCF of Cd in different parts of DR*

Treatment		$BCF_{J/S}$	$BCF_{G/S}$	$BCF_{T/S}$
CK		4.48 ± 0.17a	1.63 ± 0.08a	1.08 ± 0.10a
LM	LM-1	4.06 ± 0.08ab	1.33 ± 0.01ab	0.94 ± 0.08ab
	LM-2	3.79 ± 0.27bc	1.22 ± 0.17b	0.78 ± 0.07b
	LM-3	3.34 ± 0.33c	1.15 ± 0.20b	0.80 ± 0.08b
	LM-4	3.34 ± 0.12c	1.18 ± 0.20b	0.80 ± 0.09b
BC	BC-1	4.02 ± 0.39ab	1.33 ± 0.06b	0.97 ± 0.10ab
	BC-2	4.44 ± 0.34a	1.41 ± 0.04b	1.03 ± 0.08a
	BC-3	3.33 ± 0.31b	1.08 ± 0.06c	0.78 ± 0.06b
	BC-4	3.50 ± 0.25b	1.12 ± 0.03c	0.79 ± 0.09b

Different lowercase letters indicate statistically significant differences between treatments with the same conditioner ($p < 0.05$). The same applies below

Table 4. *The TF of Cd in different parts of DR*

Treatment		$TF_{J/T}$	$TF_{G/J}$
CK		4.15 ± 0.15b	0.36 ± 0.02a
LM	LM-1	4.31 ± 0.35ab	0.33 ± 0.04a
	LM-2	4.40 ± 0.21ab	0.32 ± 0.06a
	LM-3	4.19 ± 0.24b	0.35 ± 0.03a
	LM-4	4.19 ± 0.20b	0.35 ± 0.02a
BC	BC-1	4.16 ± 0.07a	0.33 ± 0.02a
	BC-2	4.30 ± 0.21a	0.32 ± 0.04a
	BC-3	4.28 ± 0.22a	0.32 ± 0.04a
	BC-4	4.43 ± 0.08a	0.32 ± 0.04a

Correlation analysis of Cd in different parts of DR

The total Cd, pH, DTPA-Cd, and Cd concentrations in different parts of DR exhibited significant positive correlations with the various treatments applied. Following the application of LM (*Fig. 3a*) and BC (*Fig. 3b*), a significant inverse correlation was observed between pH and DTPA-Cd, as well as Cd content in different segments of DR ($p < 0.05$). The results further demonstrated a significant positive correlation between the DTPA-Cd and Cd contents in the different components of DR ($p < 0.05$). Additionally, a significant positive correlation was observed among the Cd content in the thallus, pileus, and volva. ($p < 0.05$). In conclusion, both pH and DTPA-Cd content exerted a substantial influence on the absorption and accumulation of Cd by DR.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

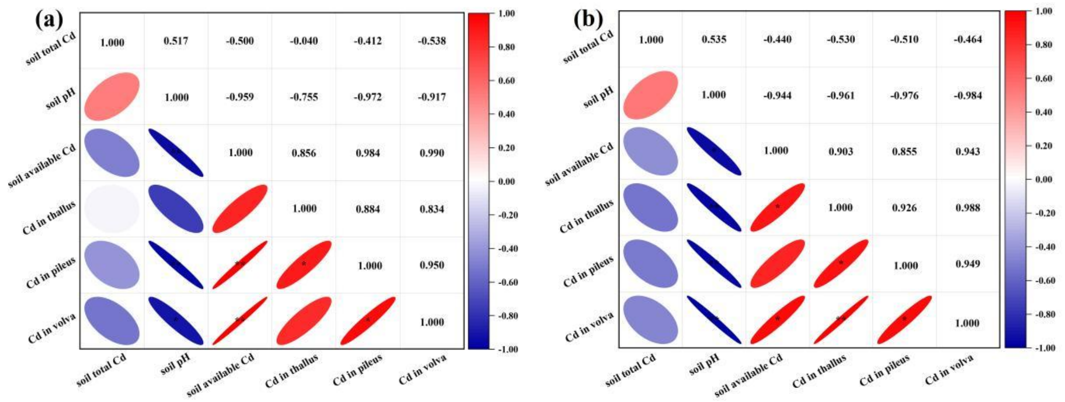

***Figure 3.** The correlation between soil Cd, pH, DTPA-Cd, and Cd contents in different parts of DR treated with Lime (a) and biochar (b) ("**" denotes a statistically significant correlation at the 0.01 bilateral level, while "*" indicates a statistically significant correlation at the 0.05 bilateral level)*

Redundancy analysis of Cd accumulation in DR

Redundancy analysis (RDA) revealed the interrelationships between soil Cd, pH, DTPA-Cd, and Cd content in different regions of DR. In LM (*Fig. 4a*), DTPA-Cd and pH accounted for 62.0% and 50.5% of the variance, respectively. However, in BC (*Fig. 4b*), these factors explained 57.0% and 72.4% of the variation. The RDA results demonstrated a strong association between DTPA-Cd, pH, and Cd accumulation across various organs in the DR.

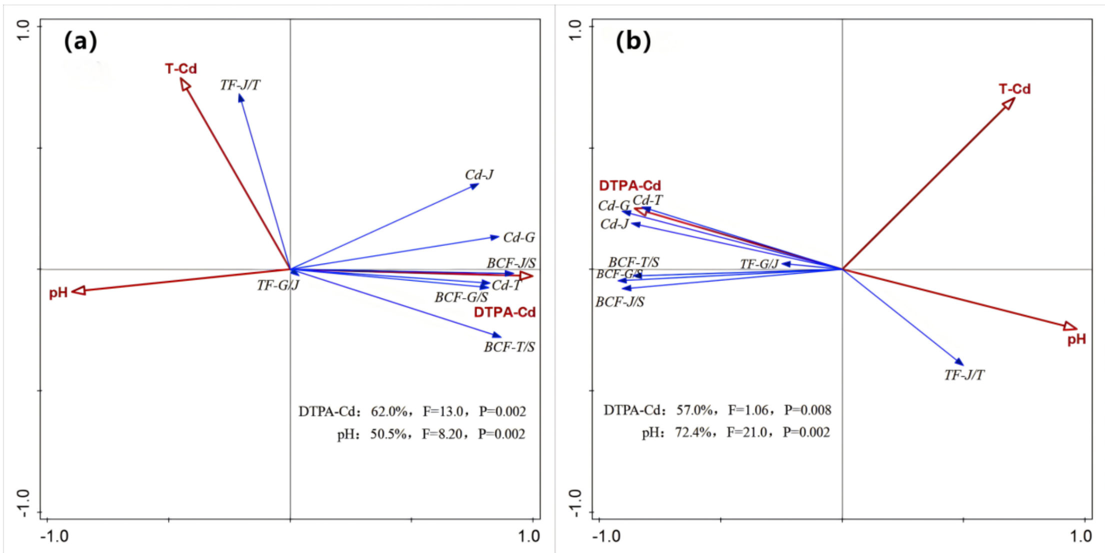

***Figure 4.** Redundancy analysis of soil Cd, available Cd, pH, and Cd accumulation in different parts of DR with lime (a) and biochar (b) was conducted*

Health risk assessment of Cd in thallus

THQ of Cd of adults or children in DR are shown in *Table 5*. Compared with CK, the THQ in LM and BC decreased for children and adults. However, the THQ of Cd was

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

greater than 1 for adults and children, indicating that adults and children were exposed to health risks associated with edible thalli. The THQ of children was higher than that of adults, indicating that children have greater health risks from Cd.

Table 5. *THQ of Cd of adults or children in DR*

Treatment		Children	Adults
	CK	10.44	7.95
LM	LM-1	9.77	7.44
	LM-2	9.78	7.45
	LM-3	8.38	6.38
	LM-4	7.93	6.03
BC	BC-1	10.22	7.78
	BC-2	10.20	7.76
	BC-3	8.30	6.32
	BC-4	8.71	6.63

Discussion

Soil remediation materials decrease the bioavailability of heavy metals in the soil and their accumulation in crops (Diels et al., 2002; Vangronsveld et al., 1996). LM neutralizes acidic substances in soil (e.g., H^+ and Alł$^+$) by releasing Ca^+ and CO_3꜀$^-$, increasing pH, and promoting the precipitation of heavy metals (e.g., Cd꜀$^+$) as hydroxides, carbonates, or phosphates, thereby reducing the bioavailability of heavy metals (Wang et al., 2021b). Soil pH in LM increased1.54-1.97, decreasing the DTPA-Cd content from 29.26% to 57.95%. The findings of the present study are consistent with those previously reported. LM neutralizes exchangeable and active acids in the soil and increases the content of Ca and Mg, resulting in reduced DTPA-Cd content (Fageria et al., 2014; Fageria, 2001). Soil pH in BC increased by 0.36-1.31, decreasing DTPA-Cd content by 0.84-38.93%. 5% BC could decrease the DTPA-Cd content by 42.7%, attributable to mineral ash in BC (Park et al., 2011). Mineral Ash is composed of alkaline oxides or carbonates of Na, K, Ca, and Mg (Sun et al., 2014; Wang et al., 2019). BC is also rich in organic acid radicals and basic groups, such as -COO- and -O-, which can combine with H^+, resulting in a higher pH and stronger cation exchange capacity (Jeffery et al., 2011). As the soil pH increased, the protonation of unsaturated bonds on the surface resulted in a negative charge, thereby facilitating metal adsorption through surface complexation. Heavy metals in soil form stable complexes with surface-bound negative free radicals, establishing enduring associations (Du et al., 1997). In soil, these complexes facilitate the stable precipitation of heavy metals in the form of hydroxides and carbonates, thereby promoting their long-term sequestration. Consequently, the heavy metal content and bioavailability of soil are diminished (He et al., 2020; Yang et al., 2018). Compared with BC, LM was more applicable in the remediation of Cd-contaminated soils with DR. The pHs of LM and BC were different. LM primarily comprised CaO, with a 12.70 pH. BC was coconut shell biomass carbon, with a pH of 10.40. The ionic radius of Ca^{2+} is close to that of Cd^{2+}, with the same charge and similar physical and chemical properties (Chen et al., 2019), which can exert a significant influence on DTPA-Cd in soil, thereby diminishing the availability of heavy metals (Huang et al., 2017; Song et al., 2008). The application of LM and BC

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146

effectively decreased Cd accumulation in DR. Compared to CK, LM of 3.0% and 5.0% had no significant difference, attributed to increased pH and decreased DTPA-Cd in the soil. The application of LM and BC decreased the accumulation and translocation of Cd in DR.

The BCF of Cd in J was significantly higher than those in G and T (*Table 3*). $TF_{J/T}$ had a greater magnitude than $TF_{G/J}$. BCF of Cd in DR was higher, indicating that DR was more likely to absorb Cd in the soil. J was more likely to accumulate Cd than G and T. Redundancy analysis revealed a significant correlation between pH, DTPA-Cd in soil, and Cd accumulation in DR. Soil pH and Cd content in different parts of DR had a significant negative correlation. DTPA-Cd and Cd content of thallus and volva had a significant positive correlation. DTPA-Cd and soil pH influenced Cd accumulation. The THQ in LM and BC decreased in children and adults associated with edible thalli. LM and BC decreased Cd accumulation in DR. The application of LM and BC decreased the accumulation and translocation of Cd in DR, which is consistent with the results of other studies (*Table 6*). 3% LM or 5% BC could be employed for Cd-contaminated soil in DR.

There are also some problems with the application of LM and BC. Long-term application of LM can lead to soil compaction, reduced aeration, and water permeability, affect the activity of soil microorganisms, and may lead to negative effects, such as the imbalance of other nutrients (Kumpiene et al., 2019). Long-term application of BC can lead to the release of harmful components, micronutrient deficiencies, and other negative effects (Xiang et al., 2021). Future studies could focus on the mechanism of heavy metal enrichment and modification materials to decrease Cd accumulation in DR.

Table 6. *Application effects of different concentrations of LM and BC on various crops in previous studies*

Material	Crop	Application concentration	Cd reduction rate in crops	pH increase	DTPA-Cd reduction rate	Reference
Lime	Brassica napus L	0.3%	74.3%	1.58	33.6%	Lei et al. (2022)
Biochar		1.0%	34.3%	0.77	16.9%	
Lime	Tea	2250 kg/hm^2	37.01%	0.48	74.08%	Liu et al. (2023)
Biochar		1050 kg/hm^2	41.45%	0.38	73.03%	
Lime	Rice	18000 kg·ha^{-1}	93.0%	1.15	64.0%	Liu et al. (2020)
Biochar		48000 kg·ha^{-1}	59.5%	0.86	61.6%	Wang et al. (2021a)

Conclusion

The application of LM and BC increased the pH and DTPA-Cd in soil. The application of LM and BC decreased the accumulation and translocation of Cd in different parts of the DR. THQ in LM and BC decreased for children and adults. However, THQ of Cd was more than 1 for adults and children. Soil pH and Cd content in different parts of DR had a significant negative correlation. DTPA-Cd and Cd content of thallus and volva had a significant positive correlation. DTPA-Cd and soil pH influenced Cd accumulation. Therefore, 3% LM or 5% BC can be employed for Cd-contaminated soil in DR. Compared with BC, LM was more applicable in the remediation of Cd-contaminated soils with DR.

Author contributions. Guihua Liu contributed to the conceptualization, methodology, data curation, and writing of the original DRaft, as well as the review and editing process. Chengwu Fan and Song Qin were involved in conceptualization, investigation, resource acquisition, and reviewing/editing of the manuscript. Guanqun Chai, Li Wang, and Ya Jiang contributed to the investigation process, methodology implementation, and data curation. Hu Wang played a role in conceptualizing the study design, conducting investigations, methodology development, implementation, funding acquisition, project administration, formal analysis, supervision and software. All authors have reviewed and approved the final manuscript.

Conflict of interests. The authors hereby affirm that they possess no known financial interests or personal relationships that could have potentially influenced the findings presented in this manuscript.

Data availability. Data will be made available on request.

REFERENCES

[1] Akkajit, P., Tongcumpou, C. (2010): Fractionation of metals in cadmium contaminated soil: relation and effect on bioavailable cadmium. – Geoderma 156(3): 126-132. https://doi.org/10.1016/j.geoderma.2010.02.007.

[2] Butnan, S., Deenik, J. L., Toomsan, B., Antal, M.J., Vityakon, P. (2015): Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy. – Geoderma 237: 105-116. https://doi.org/10.1016/j.geoderma.2014.08.010.

[3] Chen, H., Shu, F., Yang, S., Li, Y., Wang, S. (2019): Competitive inhibitory effect of calcium polypeptides on Cd enrichment of Brassia campestris L. – International Journal of Environmental Research and Public Health 16(22): 4472. https://doi.org/10.3390/ijerph16224472.

[4] Chen, X., Zhou, X., Zhao, J., Tang, X., Pasquali, M., Migheli, Q., Berg, G., Cernava, T. (2021): Occurrence of green mold disease on Dictyophora rubrovolvata caused by Trichoderma koningiopsis. – Journal of Plant Pathology 103(3): 1-4. https://doi.org/10.1007/s42161-021-00861-x.

[5] Cui, L., Noerpel, M. R., Scheckel, K. G., Ippolito, J. A. (2019): Wheat straw biochar reduces environmental cadmium bioavailability. – Environment International 126: 69-75. https://doi.org/https://doi.org/10.1016/j.envint.2019.02.022.

[6] Diels, L., Lelie, N. v. d., Bastiaens, L. (2002): New developments in treatment of heavy metal contaminated soils. – Reviews in Environmental Science and Biotechnology 1(1): 75-82. https://doi.org/10.1023/a:1015188708612.

[7] Du, F., Yang, Z., Liu, P., Wang, L. (2018): Accumulation, translocation, and assessment of heavy metals in the soil-rice systems near a mine-impacted region. – Environmental Science and Pollution Research International 25(32): 32221-32230. https://doi.org/10.1007/s11356-018-3184-7.

[8] Du, Q., Sun, Z., Forsling, W., Tang, H. (1997): Acid-base properties of aqueous lllite surfaces. – Journal of Colloid and Interface Science 187(1): 221-231. https://doi.org/https://doi.org/10.1006/jcis.1996.4631.

[9] Fageria, N. K. (2001): Effect of liming on upland rice, common bean, corn, and soybean production in cerrado soil. – Pesquisa Agropecuaria Brasileira 36(11): 1419-1424. https://doi.org/https://doi.org/10.1590/S0100-204X2001001100013.

[10] Fageria, N. K., Moreira, A., Moraes, L. A. C., Moraes, M. F. (2014): Influence of lime and gypsum on yield and yield components of soybean and changes in soil chemical properties. – Communications in Soil Science and Plant Analysis 45(3): 271-283. https://doi.org/10.1080/00103624.2013.861906.

[11] Feng, Y., Yang, J., Liu, W., Yan, Y., Wang, Y. (2020): Hydroxyapatite as a passivator for safe wheat production and its impacts on soil microbial communities in a Cd-

contaminated alkaline soil. – Journal of Hazardous Materials 404(PB): 124005. https://doi.org/10.1016/j.jhazmat.2020.124005.
[12] Fu, Z., Liu, G., Wang, L. (2020): Assessment of potential human health risk of trace element in wild edible mushroom species collected from Yunnan Province, China. – Environmental Science and Pollution Research 27(23): 29218-29227. https://doi.org/10.1007/s11356-020-09242-w.
[13] He, Y., Lin, H., Jin, X., Dong, Y., Luo, M. (2020): Simultaneous reduction of arsenic and cadmium bioavailability in agriculture soil and their accumulation in Brassica chinensis L. by using minerals. – Ecotoxicology and Environmental Safety 198: 110660. https://doi.org/10.1016/j.ecoenv.2020.110660.
[14] Huang, D., Gong, X., Liu, Y., Zeng, G., Lai, C., Bashir, H., Zhou, L., Wang, D., Xu, P., Cheng, M., Wan, J. (2017): Effects of calcium at toxic concentrations of cadmium in plants. – Planta 245(5): 863-873. https://doi.org/10.1007/s00425-017-2664-1.
[15] Jeffery, S., Verheijen, F. G. A., Velde, M. v. d., Bastos, A. C. (2011): A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. – Agriculture, Ecosystems and Environment 144(1): 175-187. https://doi.org/10.1016/j.agee.2011.08.015.
[16] Jiang, L., Yi, X., Xu, B., Wang, W., Lai, K. (2019): Soil treatment and crop rotation for in situ remediation of heavy metal-contaminated agricultural soil in gold mining areas. – Human and Ecological Risk Assessment: An International Journal 25(1-2): 374-392. https://doi.org/10.1080/10807039.2019.1568856.
[17] Kumpiene, J., Antelo, J., Brännvall, E., Carabante, I., Ek, K., Komárek, M., Söderberg, C., Wårell, L. (2019): In situ chemical stabilization of trace element-contaminated soil—field demonstrations and barriers to transition from laboratory to the field. A review. – Applied Geochemistry 100: 335-351. https://doi.org/10.1016/j.apgeochem.2018.12.003.
[18] Lei, M., Li, Z., Zhang, B., Wang, X., Tie, B., Ayaz, T., Lu, X. (2022): Mechanisms of stress alleviation after lime and biochar applications for brassica napus L. in cadmium-contaminated soil. – Adsorption Science & Technology 2022: 4195119. https://doi.org/10.1155/2022/4195119.
[19] Liu, B., Huang, Q., Cai, H., Guo, X., Wang, T., Gui, M. (2015): Study of heavy metal concentrations in wild edible mushrooms in Yunnan Province, China. – Food Chemistry 188: 294-300. https://doi.org/10.1016/j.foodchem.2015.05.010.
[20] Liu, W., Tang, Y., Ma, J., Zhang, W., Liao, S., Cui, S., Ye, Z., Liu, D. (2023): Effects of biochar and inorganic amendments on soil fertility, tea yield, and quality in both Pb–Cd-contaminated and acidified tea plantations. – Journal of Soils and Sediments 23(9): 3275-3284. https://doi.org/10.1007/s11368-023-03523-w.
[21] Liu, Z., Huang, Y., Ji, X., Xie, Y., Peng, J., Eissa, M. A., Fahmy, A. E., Elwafa, S. F. A. (2020): Effects and mechanism of continuous liming on cadmium immobilization and uptake by rice grown on acid paddy soils. – Journal of Soil Science and Plant Nutrition 20(4): 1-13. https://doi.org/10.1007/s42729-020-00297-9.
[22] Lombi, E., Zhao, F., Wieshammer, G., Zhang, G., McGrath, S. P. (2002): In situ fixation of metals in soils using bauxite residue: biological effects. – Environmental Pollution 118(3): 445-452. https://doi.org/10.1016/s0269-7491(01)00295-0.
[23] Oliver, D. P., Tiller, K. G., Conyers, M. K., Slattery, W. J., Alston, A. M., Merry, R. H. (1996): Effectiveness of liming to minimise uptake of cadmium by wheat and barley grain grown in the field. – Australian Journal of Agricultural Research 47(7): 1181-1193. https://doi.org/10.1071/AR9961181.
[24] Park, J. H., Choppala, G. K., Bolan, N. S., Chung, J. W., Chuasavathi, T. (2011): Biochar reduces the bioavailability and phytotoxicity of heavy metals. – Plant and Soil 348(1-2): 439-451. https://doi.org/10.1007/s11104-011-0948-y.
[25] Peng, Y., Yang, R., Jin, T., Chen, J., Zhang, J. (2018): Risk assessment for potentially toxic metal(loid)s in potatoes in the indigenous zinc smelting area of northwestern

Guizhou Province, China. – Food and Chemical Toxicology 120: 328-339. https://doi.org/10.1016/j.fct.2018.07.026.

[26] Puschenreiter, M., Horak, O., Friesl, W., Hartl, W. (2005): Low-cost agricultural measures to reduce heavy metal transfer into the food chain—a review. – Plant, Soil and Environment 51(1): 1-11. https://doi.org/10.17221/3549-pse.

[27] Qin, G., Liu, J., Zou, K., He, F., Li, Y., Liu, R., Zhang, P., Zhao, G., Wang, T., Chen, B. (2024): Analysis of heavy metal characteristics and health risks of edible mushrooms in the mid-western region of China. – Scientific Reports 14(1): 26960. https://doi.org/10.1038/s41598-024-78091-1.

[28] Sharma, D., Inbaraj, M. P., Naz, A., Chowdhury, A. (2024): Fate, source apportionment and fractionation of potentially toxic elements in agricultural soil around a densely populated, semiarid urban center of India: baseline study and ecological risk assessment. – Environmental Geochemistry and Health 46(6): 207. https://doi.org/10.1007/s10653-024-01997-2.

[29] Song, W., Zhang, Z., Shao, H., Guo, X., Cao, H., Zhao, H., Fu, Z., Hu, X. (2008): Relationship between calcium decoding elements and plant abiotic-stress resistance. – International Journal of Biological Sciences 4(2): 116-125. https://doi.org/10.7150/ijbs.4.116.

[30] Sun, C., Zhu, S., Zhao, B., Li, W., Gao, X., Wang, X. (2019): Effect of land use conversion on surface soil heavy metal contamination in a typical karst plateau lakeshore wetland of southwest China. – International Journal of Environmental Research and Public Health 17(1): 84. https://doi.org/10.3390/ijerph17010084.

[31] Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., Chen, H., Yang, L. (2014): Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. – Chemical Engineering Journal 240: 574-578. https://doi.org/10.1016/j.cej.2013.10.081.

[32] Vangronsveld, J., Colpaert, J. V., Tichelen, K. K. V. (1996): Reclamation of a bare industrial area contaminated by non-ferrous metals: physico-chemical and biological evaluation of the durability of soil treatment and revegetation. – Environmental Pollution 94(2): 131-140. https://doi.org/https://doi.org/10.1016/S0269-7491(96)00082-6.

[33] Wang, H., Cai, N., Gong, S., Zhou, J., He, T., Wang, B., Fu, T. (2023): Establishment and optimization of soil Cd risk threshold in typical karst area with potato production, China. – Bulletin of Environmental Contamination and Toxicology 110(1): 34. https://doi.org/10.1007/s00128-022-03640-1.

[34] Wang, H., Teng, L., Mao, X., He, T., Fu, T. (2024): Comparing the effects of lime soil and yellow soil on cadmium accumulation in rice during grain-filling and maturation periods. – Plants (Basel, Switzerland) 13(15): 2018. https://doi.org/10.3390/PLANTS13152018.

[35] Wang, S., Li, B., Zhu, H., Shen, J., Zhu, Q., Huang, D., Xu, C., Zhang, Q., Fang, Z. (2021a): Long-term effects of biochar on trace metals accumulation in rice grain: a 7-year field experiment. – Agriculture, Ecosystems and Environment 315: 107446. https://doi.org/10.1016/j.Agee.2021.107446.

[36] Wang, Y., Wang, H., Tang, C., Gu, K., Shi, B. (2019): Remediation of heavy metal contaminated soils by biochar: a review. – Environmental Geotechnics 9(3): 135-148. https://doi.org/10.1680/jenge.18.00091.

[37] Wang, Y., Yao, Z., Zhan, Y., Zheng, X., Zhou, M., Yan, G., Wang, L., Werner, C., Butterbach-Bahl, K. (2021b): Potential benefits of liming to acid soils on climate change mitigation and food security. – Global Change Biology 27(12): 2807-2821. https://doi.org/10.1111/gcb.15607.

[38] Xiang, L., Liu, S., Ye, S., Yang, H., Song, B., Qin, F., Shen, M., Tan, C., Zeng, G., Tan, X. (2021): Potential hazards of biochar: the negative environmental impacts of biochar applications. – Journal of hazardous materials 420: 126611. https://doi.org/10.1016/j.Jhazmat.2021.126611.

[39] Xiao, R., Huang, Z., Li, X., Chen, W., Deng, Y., Han, C. (2017): Lime and phosphate amendment can significantly reduce uptake of Cd and Pb by field-grown rice. – Sustainability 9(3): 430. https://doi.org/10.3390/su9030430.

[40] Yadav, A. K., Shekhar, S., Naz, A., Koul, M., Yadav, H. K., Kumar, P., Chowdhury, A. (2024): Potential toxic elements in groundwater: a health risk in parts of northern Delhi. – Proceedings of the Indian National Science Academy 91(3): 1-16. https://doi.org/10.1007/s43538-024-00358-y.

[41] Yang, X., Igalavithana, A. D., Oh, S., Nam, H., Zhang, M., Wang, C., Kwon, E. E., Tsang, D. C. W., Ok, Y. S. (2018): Characterization of bioenergy biochar and its utilization for metal/metalloid immobilization in contaminated soil. – Science of the Total Environment 640: 704-713. https://doi.org/10.1016/j.scitotenv.2018.05.298.

[42] Zhang, D., Li, T., Wu, X., Wang, Y. (2021): Effect of amendments (lime–zeolite–biochar) on the immobilization of Cd and Pb in a contaminated acidic soil. – IOP Conference Series: Earth and Environmental Science 742(1): 012016. https://doi.org/10.1088/1755-1315/742/1/012016.

[43] Zhang, J., Li, H., Zhou, Y., Dou, L., Cai, L., Mo, L., You, J. (2018): Bioavailability and soil-to-crop transfer of heavy metals in farmland soils: a case study in the Pearl River Delta, South China. – Environmental Pollution 235: 710-719. https://doi.org/10.1016/j.envpol.2017.12.106.

[44] Zhang, X., Chen, D., Zhong, T., Zhang, X., Cheng, M., Li, X. (2015): Assessment of cadmium (Cd) concentration in arable soil in China. – Environmental science and pollution research international 22(7): 4932-4941. https://doi.org/10.1007/s11356-014-3892-6.

[45] Zhang, Y., Wu, Y. E., Yang, A., Wang, J., Zhang, K., Hu, D. (2017): Assessment of cadmium content of potato grown in Weining County, Guizhou Province, China. – Environmental Monitoring and Assessment 189(5): 226. https://doi.org/10.1007/s10661-017-5950-2.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_11331146