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Original Research

Profile Reconstruction via Deep Soil Mixing: A Practical Strategy for Mitigating Cadmium and Copper Availability in Naturally Enriched Vegetable Soils of Southwest China

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Abstract

High natural heavy metal levels in Southwest China's soils often lead to farmland contamination, and developing cost-effective risk mitigation strategies is crucial for safe agricultural production. This study evaluated profile reconstruction of a copper (Cu)- and cadmium (Cd)-contaminated vegetable production base in Kunming via deep soil mixing. Soil profile analysis revealed a clear surface accumulation of Cd and available Cu/Cd in the topsoil. Deep plowing to a depth of 50 cm effectively reduced the available Cu and Cd concentrations in the newly formed topsoil from 5.60±1.81 mg kg^{-1} to 2.09±1.77 mg kg^{-1} (a 63% reduction) and from 0.143±0.064 mg kg^{-1} to 0.032±0.035 mg kg^{-1} (a 78% reduction), respectively. The intervention reduced the mean total Cd concentration to 0.22±0.11 mg kg^{-1}, alongside a drop in the Cd exceedance rate from 80% to 20%. Soil pH and phosphorus/potassium contents remained stable; however, levels of soil organic matter and available nitrogen declined significantly. Field experiments confirmed that deep plowing effectively reduced the Cu and Cd contents in the edible parts of vegetables. Therefore, deep tillage presents a practical and rapid strategy for mildly contaminated sites with vertical metal accumulation, allowing for simultaneous production and remediation.

Keywords: deep soil mixing, heavy metal contamination, copper, cadmium; soil fertility

Introduction

The acceleration of industrialization and urbanization has exacerbated heavy metal pollution in agricultural soils worldwide [1-3]. In China, the 2014 National Soil Pollution Status Investigation Bulletin revealed that 19.4% of the surveyed agricultural soils exceeded the national environmental quality standards, with cadmium (Cd), nickel (Ni), and arsenic (As) being the predominant pollutants [4]. Heavy metal accumulation varies significantly across land use types; vegetable fields and paddy soils demonstrate

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higher contamination levels than other croplands [5, 6]. Vegetables are a primary source of dietary nutrition, but elevated concentrations of heavy metals in soil can reduce crop yield and quality. When vegetables absorb and accumulate harmful heavy metals in their tissues, including both the edible and inedible parts, the resulting levels may exceed recommended safety limits [7-9]. This poses a direct threat to human health through bioaccumulation in the food chain [10, 11]. These concerns underscore the urgent need to develop cost-effective remediation strategies for contaminated vegetable fields to safeguard agricultural productivity and food safety.

Numerous remediation technologies for heavy metal contamination in agricultural soils have been developed globally, encompassing physical, chemical, biological, and combined approaches [12-14]. While most remediation efforts have focused on severely contaminated agricultural lands used for large-scale production, research on small-to-medium vegetable farms remains limited. Vegetable fields represent a distinct agroecosystem characterized by intensive cultivation practices, which often lead to moderate-to-high levels of heavy metal accumulation due to high replanting indices and frequent farming operations [15]. The accumulation of heavy metals in vegetables is influenced by both crop species and the bioavailability of these metals in the soil [16, 17]. The bioavailability of soil heavy metals is not only determined by the total amount of soil heavy metals, but is also influenced by the physical and chemical properties of the soil, such as pH and organic matter content [18-20]. Current mitigation strategies include the application of soil amendments (e.g., phosphate-based materials), which effectively immobilize metals, the cultivation of low-accumulating vegetable varieties, and optimized agronomic practices [7, 15]. While effective, many of these strategies require repeated applications or management cycles and may involve ongoing costs or potential secondary impacts.

In practical applications, optimal remediation technologies must be selected based on comprehensive considerations of economic factors, technical requirements, climatic conditions, and operational practicality for local farmers. Among various agricultural management practices, tillage (e.g., utilizing rotary tillers, subsoilers, integrated tillage machines) represents a fundamental intervention for soil restructuring. Conventional tillage is controversial due to its potential adverse effects, such as soil moisture loss, increased temperature, and elevated greenhouse gas emissions [21]. Nevertheless, deep tillage has been proposed as a mechanical alternative and has shown potential for enhancing crop production and remediating heavy metal-contaminated soils [22-25]. Although deep tillage requires measurable energy input, raising concerns regarding its carbon footprint and long-term sustainability, and may temporarily increase soil susceptibility to erosion, its use can still be justified in specific contexts where rapid risk mitigation is prioritized. Meta-analyses have demonstrated that conventional deep tillage generally increases crop yields when performed at depths of approximately 25 to 35 cm [26-29]. However, beyond this range, deeper plowing may result in lower yields compared to conventional tillage practices. When applied to contaminated soils, this technique can physically redistribute heavy metals into deeper soil layers, thereby reducing their bioavailability without compromising agricultural productivity [30]. Following such an initial intervention, fields can subsequently be managed under more sustainable practices, such as the establishment of vegetative cover to prevent soil erosion and promote soil structure recovery [31]. Although numerous studies have examined the effects of deep tillage on soil fertility and crop yields [32, 33], research focusing on its application as a heavy metal remediation technique remains relatively limited.

Located in the southwestern part of China, Yunnan Province boasts favorable climatic and geographical conditions that are highly conducive to the development of the vegetable industry [34]. The predominant vegetable species cultivated in this region are those with large leaves, including cabbage and lettuce. However, the natural background concentrations of heavy metals in Yunnan's soils are notably high, primarily due to the weathering of parent rocks [35]. This situation has been further exacerbated by intensive nonferrous metal mining and smelting activities [36, 37]. Data from the first national soil pollution survey in China revealed that the mean Cu and Cd concentrations in Yunnan Province soils (n = 1505) reached 60.3 mg kg^{-1} (range: 18.3~130.0 mg kg^{-1}) and 0.179 mg kg^{-1} (range: 0.035~0.390 mg kg^{-1}), respectively, exceeding the average background values in China (Cu: 22.6 mg kg^{-1}; Cd: 0.097 mg kg^{-1}) [38]. In particular, Yunnan Province recorded the highest soil Cu concentrations among all surveyed provinces. However, investigations and studies have shown that the concentrations of Cd, Cu, and other heavy metals in the edible parts of some vegetables in Kunming City and the surrounding areas in Yunnan Province exceeded the national food hygiene standards and green vegetable standards, and long-term consumption of these vegetables poses a risk to human health [39, 40]. This study assessed the heavy metal pollution status in a vegetable base in Kunming City, analyzing the distribution of Cu, Cd, and their available forms within the soil profile. Subsequently, deep plowing was implemented as a risk mitigation practice, and its effectiveness in reducing Cu and Cd availability, their accumulation in vegetables, and the subsequent impacts on soil fertility were evaluated. The objective was to verify the potential of deep tillage as a risk mitigation strategy for maintaining agricultural production in vegetable fields with mild to moderate contamination characterized by vertical heavy metal accumulation.

Materials and Methods

Study Area

The experimental site was located in a vegetable production base within the Songhuaba watershed, Panlong District, Kunming City, Yunnan Province, China (25°17’34”N, 102°52’39”E; altitude 1995 m) (Fig. 1). This basin, which serves as the drainage area for the Panlong River – the main tributary flowing into Dianchi Lake – is situated north of Kunming City. The region has a central subtropical plateau monsoon climate, characterized by an average annual temperature of 14.9°C, annual precipitation of 1000.5 mm, annual sunshine duration of 2327.5 hours, and annual evaporation of 1856.4 mm. Most rainfall occurs between May and September.

Owing to these favorable agro-climatic conditions, the Songhuaba watershed has become one of the most important vegetable cultivation bases in Yunnan Province, supporting vegetable production as a distinctive agricultural sector in the Yunnan plateau region. However, long-term intensive cultivation practices (more than 4 cycles per year), combined with heavy reliance on chemical and organic fertilizers, have led to significant nutrient accumulation in the topsoil.

Pollution Investigation

The soil type in this area is red soil (Ultisols). A background soil investigation was conducted in a 10-hectare vegetable production base. Following the principle of collecting one soil sample per hectare, 10 sampling points were established in March 2020 (Fig. 1). The geographical coordinates of the sampling area ranged from 25.203162°N to 25.204021°N in latitude and from 102.878464°E to 102.880117°E in longitude (GCJ02 coordinate system). Soil samples were collected from the 0~20 cm depth (representing the topsoil before deep plowing). At each sampling point, five subsamples were collected using a plum-shaped distribution pattern. After thorough homogenization, approximately 500 g of soil was obtained using the quartering method. After removal of debris (e.g., stones, and plant and animal residues), the samples were stored in polypropylene plastic bags for subsequent analysis. The analyses included soil pH, soil organic matter (SOM) content, and the contents of total and available nitrogen (N), phosphorus (P), and potassium (K), as well as the total concentrations of heavy metals (Cu, Cd, Pb, Ni, Zn, As, Hg, and Cr). Based on the initial site characterization and as further detailed in the Results section, the subsequent study specifically focused on Cu and Cd, as these were the only metals found to exceed the Chinese national standard (GB 15618-2018), thereby constituting the primary contamination risk at the site.

Additionally, three of the 10 sampling points were randomly selected for soil profile analysis (0~100 cm depth). A Luoyang shovel was used to collect mixed soil samples from five depth intervals: 0~10 cm, 10~20 cm, 20~50 cm, 50~70 cm, and 70~100 cm. Total Cu, available Cu, total Cd, and available Cd concentrations were analyzed for each layer.

Deep Plowing

Based on the vertical distribution characteristics of heavy metals in the soil profile, deep plowing was performed on April 6, 2020, using a tractor to reach a depth of 50 cm. This tillage depth was selected to effectively dilute contaminants, as supported by soil profile analysis (Fig. 2), while also considering practical feasibility. The defined depths for topsoil (0~20 cm) and subsoil (20~50 cm) align with conventional agronomic practices in the region [41, 42]. Following the deep plowing, soil samples were collected from the topsoil and the subsoil to determine the total Cu, available Cu, total Cd, and available Cd concentrations, as well as soil properties (pH and organic matter concentration, etc.).

Determination of Soil Properties

Air-dried soil samples were homogenized and passed through a 2 mm nylon sieve for subsequent analysis of soil properties [37, 43]. Soil pH was measured potentiometrically using a pH meter (FE28, Mettler Toledo, Switzerland) with a soil/water ratio of 1:2.5. Soil organic matter (SOM) contents were determined

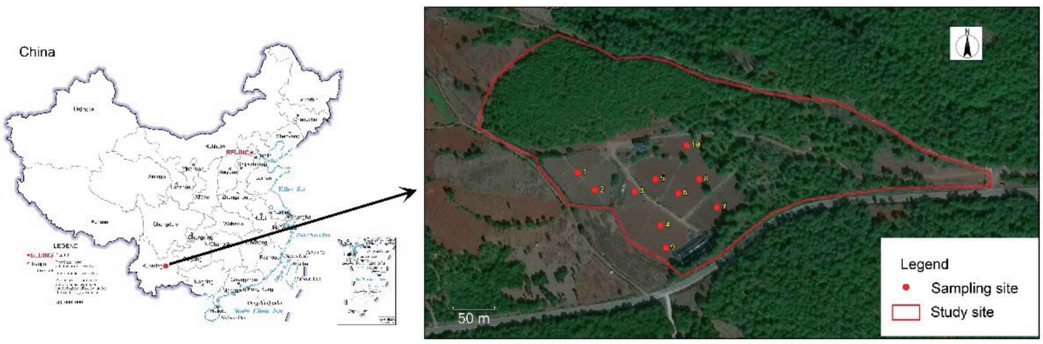

Fig. 1. Map of the sampling sites in the study area.

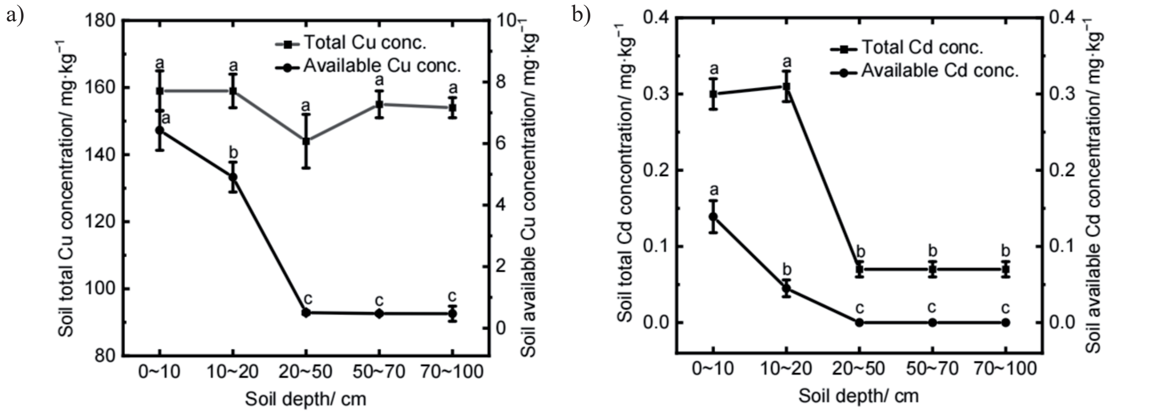

Fig. 2. a)Vertical distribution of soil total Cu and available Cu, and b) soil total Cd and available Cd concentrations in soil profiles. Different lowercase letters indicate significant differences among soil depths (p<0.05). Conc.: concentration.

by the $K_2Cr_2O_7$ oxidation titration (exogenous heat) method [44]. Soil total N content was analyzed using the acid digestion-Kjeldahl method [45] and available N content was measured by the alkaline hydrolysis diffusion method [43]. Soil total P content and available P content were extracted using H_2SO_4-$HClO_4$ and HCl-NH_4F, respectively, and then the Pi concentration was measured using the molybdate blue colorimetric method [46]. Soil total K content and available K content were extracted using H_2SO_4-$HClO_4$ and ammonium acetate, respectively, and then the K concentration was determined by flame photometry (FP640, Shanghai, China).

Determination of Soil Heavy Metal Concentrations

The powdered samples (0.2 g) were digested using a ternary mixture of trace metal grade HF, HNO_3, and $HClO_3$ in Teflon crucibles. The digestion liquids were evaporated to near dryness to remove HF, and the residues were subsequently re-dissolved in dilute HNO_3 and diluted to 50 mL with triple-distilled water in volumetric flasks. The resulting solutions were filtered and stored at 4ºC before analysis. The available concentrations of Cu and Cd refer to the bioavailable fractions of these metals, which represent the chemical forms that are mobile and potentially accessible for plant uptake [47]. These available concentrations were determined using the diethylenetriamine pentaacetic acid (DTPA) solution extraction method [48]. The metal concentrations (Cu, Cd, Pb, Ni, Zn, As, Hg, and Cr) were then quantified by inductively coupled plasma-mass spectrometry (ICP-MS) (NexION 2000, PerkinElmer, USA) [38]. For quality control, a soil certified reference material (GBW07405, National Research Center for Certified Reference Materials, China) was analyzed throughout the analytical process. The analytical precision, evaluated through repeated measurements (n = 5) of the certified reference material, was below 10% (relative standard deviation) for all elements.

Evaluation of Heavy Metal Pollution Index and Potential Ecological Risk

The heavy metal pollution index was assessed using the single pollution index (P_i), calculated as follows:

$$P_i = C_i/S_i$$

Where C_i represents the measured concentration of a heavy metal in the soil samples (mg kg^{-1}), and S_i denotes the corresponding reference value (mg kg^{-1}) [1]. The reference values were based on the soil pollution risk screening values specified in the "soil pH and land type in the Soil Environmental Quality Agricultural Land Soil Pollution Risk Control Standard (GB 15618-2018)", which are determined according to soil pH and land use type. The pollution degree was classified as follows: P_i: $P_i \leq 1$, unpolluted; $1 < P_i \leq 2$, low pollution; $2 < P_i \leq 3$, moderate pollution; $P_i > 3$, strong pollution [49].

Potential ecological risk was evaluated according to the method established by Hakanson using the risk index (E_i) for a single heavy metal[50]:

$$E_i = T_i \times C_i/S_i$$

Where E_i is the potential ecological risk factor for a specific heavy metal, T_i is its toxicity response coefficient (the T_i values for Cd and Cu were set as 30 and 5, respectively). The variables C_i and S_i are as defined above. The risk level was classified based on the calculated E_i value as follows: $E_i < 40$, low risk; $40 \leq E_i < 80$, medium risk; $80 \leq E_i < 160$, high risk; $160 \leq E_i < 320$, very high risk; $E_i \geq 320$, extremely high risk [51].

Determination of Cu and Cd Content in Edible Portions of Fresh Vegetables

This study was conducted within a remediation demonstration project, where most of the vegetable field had been deeply plowed. To evaluate the effect of deep plowing on heavy metal accumulation in vegetables, three adjacent, unremediated plots (each 0.3 hectares), located near the remediation site, were selected as the control (CK) areas. Vegetable cultivation experiments were conducted from 2020 to 2022. For each vegetable species, three replicate plots (n = 3) were established in both the deep plowing treatment area and the adjacent control (CK) area. The following vegetable species were selected to evaluate the effect of deep plowing on the accumulation of Cu and Cd in fresh vegetables: Chinese flowering cabbage (*Brassica parachinensis* L. H. Bailey), Chinese kale (*Brassica alboglabra* Bailey), head lettuce (*Lactuca sativa* var. *capitata* L.), faba bean (*Vicia faba* L.), pepper (*Capsicum annuum* L.), and tomato (*Solanum lycopersicum* L.). Based on the conventional vegetable cultivation practices of local farmers, base fertilizer (nitrogen, phosphorus, and potassium) was applied according to vegetable type, with urea supplemented as needed. A uniform fertilization regimen was maintained across all treatments for each vegetable variety. At harvest, six plants per vegetable type were randomly selected, and their edible parts were collected for Cu and Cd content analysis. The edible tissues were washed, blotted dry with filter paper, accurately weighed, oven-dried, ground using a mill, and sieved through a 0.25 mm mesh for subsequent use. A 0.5 g aliquot of each sample was digested with a mixture of ultrapure HNO_3 and H_2O_2 (4:3, *v*/*v*) in a digestion tube. The digested solution was filtered and diluted to 50 mL in a volumetric flask. Concentrations of Cu and Cd were quantified using inductively coupled plasma-mass spectrometry (ICP-MS, NexION 2000, PerkinElmer, USA). For quality assurance, a plant certified reference material (cabbage material, GBW10014, National Research Center for Certified Reference Materials, China) was analyzed alongside the samples. The standard deviations of all elemental measurements were within 10%.

Data Processing and Analysis

All data are expressed as the mean ± standard deviation (SD). Statistical analyses were performed using IBM SPSS statistical software (version 22). To evaluate differences in total and available concentrations of Cd and Cu in soil profiles, a one-way analysis of variance (ANOVA) was used, followed by the least significant difference (LSD) test for multiple comparisons. Pairwise comparisons between treatment groups were conducted using t-tests.

Results

Soil Fertility and Heavy Metal Contamination Status of Topsoil in the Vegetable Field

First, we evaluated the soil fertility and heavy metal contamination status of the topsoil in the vegetable field investigated in this study. The results showed that the soil pH values of the vegetable field ranged from 6.16 to 8.14, with an average value of 7.47, indicating that the soils were mainly in the neutral pH range (pH 6.5~7.5). The average fertility indicators of the soils were as follows: organic matter 37.9 g kg^{-1}, total nitrogen 1.82 g kg^{-1}, available nitrogen 136.3 mg kg^{-1}, total phosphorus 953 mg kg^{-1}, available phosphorus 10.7 mg kg^{-1}, total potassium 8.5 g kg^{-1}, and available potassium 508 mg kg^{-1}. The average concentrations of total heavy metals in the soils were as follows: Cd 0.38 mg kg^{-1}, Hg 0.22 mg kg^{-1}, As 10.37 mg kg^{-1}, Pb 23.4 mg kg^{-1}, Cr 89 mg kg^{-1}, Cu 163 mg kg^{-1}, Ni 57 mg kg^{-1}, Zn 123 mg kg^{-1} (n = 10). According to the national standard in China, Soil Environmental Quality – Risk Control Standard for Soil Contamination of Agricultural Land (GB 15618-2018), the Cu and Cd concentrations in the soils of this plot exceeded the risk screening value for heavy metal contamination risk in agricultural land, while the other heavy metal concentrations did not exceed the risk screening value.

Due to the high soil Cd and Cu concentrations, which may result in excessive heavy metal accumulation in cultivated vegetables, we conducted a detailed analysis of the Cd and Cu levels in the topsoil (0~20 cm depth) of the vegetable field. The results showed that the total Cu and Cd concentrations ranged from 144 to 176 mg kg^{-1} and 0.18 to 0.48 mg kg^{-1}, with coefficients of variation (CV) of 6.52% and 23.15%, respectively (Table 1). These low CV values indicate a relatively uniform distribution of Cu and Cd in the surface soil layer. In contrast, the available Cu and Cd concentrations ranged from 1.77 to 7.21 mg kg^{-1} and 0.024 to 0.211 mg kg^{-1}, with averages of 5.60 mg kg^{-1} and 0.143 mg kg^{-1}, respectively. The CV values for the available Cu and Cd were 32.38% and 44.71%, indicating moderate to high variability. This suggests spatial heterogeneity in the bioavailability of these metals within the surface soil of the vegetable plot.

The potential ecological risk of Cu and Cd contamination in the vegetable field soil was evaluated. Based on the risk screening values specified in China's Soil Environmental Quality-Risk Control Standard for Soil Contamination of Agricultural Land (GB 15618-2018), the mean surface soil (0~20 cm) concentrations of both metals exceeded their respective risk screening thresholds, with exceedance rates of 100% for Cu and 80% for Cd. However, all sampling points showed Cd concentrations below the standard's risk intervention value. The single-factor pollution index averaged 1.63 for Cu and 1.26 for Cd, indicating a low level of pollution for both metals. In terms of potential ecological risk, Cu posed a low risk, whereas Cd presented a moderate risk. In summary, the vegetable field exhibits mild contamination by both Cu and Cd, with Cu showing a higher degree of pollution based on the pollution index, while Cd presents a greater ecological risk.

Table 1. Summary statistics of copper and cadmium concentrations in the topsoil of the vegetable field.

Element	Heavy metal concentrations (n = 10)					Exceedance rate[1] (%)		P_i (Pollution degree)	E_i (Potential ecological risk)
	Min (mg kg^{-1})	Max (mg kg^{-1})	Mean (mg kg^{-1})	Stdev	CV (%)	Risk screening value	Risk intervention value		
Cu	144	176	163	11	6.52	100	-	1.63±0.11 (Low)	8.13±0.53 (Low)
Available Cu	1.77	7.21	5.60	1.81	32.38			-	
Cd	0.18	0.48	0.38	0.09	23.15	80	0	1.26±0.29 (Low)	43.80±13.26 (Medium)
Available Cd	0.024	0.211	0.143	0.064	44.71			-	

Note: The mean and standard deviation were calculated from 10 sampling points. According to the risk screening values and risk intervention values for soil contamination of agricultural land in the national standard (GB 15618-2018), the exceedance rate (%) was calculated. The risk screening value for Cu is 100 mg·kg^{-1}, and the risk screening value and risk intervention value for Cd are 0.3 mg·kg^{-1} and 3.0 mg·kg^{-1}, respectively. Min: minimum; Max: maximum; Stdev: standard deviation; CV (%): coefficient of variance; $P_{i:}$ single pollution index; E_i: potential ecological risk.

Vertical Distribution of Cu and Cd in Vegetable Field Soil Profiles

To determine appropriate restoration measures for the contaminated vegetable field, further analysis was conducted on the soil profile characteristics. The Cu and Cd concentrations in the soil of this plot were relatively uniform horizontally, so a random vertical profile of 100 cm was selected from the central experimental area for detailed characterization. As shown in Fig. 2, there was no significant change in soil Cu concentration with increasing soil depth. The average total Cu concentration was 154 mg kg^{-1}, which was higher than the risk screening value of 100 mg kg^{-1} (Fig. 2a)). However, the available Cu concentration in the soil decreased significantly with increasing soil depth. Available Cu concentration was 4.91 mg kg^{-1} at 10~20 cm and only 0.504 mg kg^{-1} at 20~50 cm, an 89.7% decrease. Notably, soil Cd concentration significantly decreased with increasing soil depth (Fig. 2b)). The average soil Cd concentration at 10~20 cm was 0.31 mg kg^{-1}, while the average soil Cd concentration at 20~50 cm was only 0.07 mg kg^{-1}, a decrease of 77.5%. The concentration of available Cd in soil also significantly decreased with increasing soil depth, and the concentration of available Cd in soil was extremely low at 20~50 cm, below the Cd detection limit (0.007 mg kg^{-1}). In summary, the Cd concentration and available Cu and Cd concentrations in the soil of the vegetable field all decreased with increasing soil depth. Vertically, the soil profile showed a surface aggregation pattern, with higher concentrations above and lower below, which is suitable for deep plowing as a soil risk mitigation strategy. Based on the distribution characteristics of heavy metals in the soil mentioned above, it was speculated that a tillage depth of 50 cm could significantly reduce the Cd concentration and available Cd and Cu concentrations in the 0~20 cm tillage layer, achieving the goal of soil remediation. Therefore, this study used excavators to deeply cultivate and restore the vegetable field, with a cultivation depth of 50 cm.

Effect of Deep Plowing on Cu and Cd Concentrations in Topsoil and Subsoil Layers

The alterations in soil Cu, available Cu, Cd, and available Cd concentrations before and after deep plowing are presented in Fig. 3. The results demonstrate that total Cu concentrations in both the topsoil (0~20 cm) and subsoil layer (20~50 cm) remained statistically unchanged after deep plowing, reflecting the uniform vertical distribution of Cu within the study area (Fig. 3a)). Conversely, the available Cu concentration exhibited a substantial decline (p<0.001) in both layers following deep plowing. Specifically, the mean available Cu concentration in the topsoil decreased by 63%, from 5.60±1.81 mg kg^{-1} to 2.09±1.77 mg kg^{-1} (Fig. 3b)). For Cd, both the total and available Cd concentrations in the topsoil underwent a significant decrease after deep plowing (p<0.01 and p<0.001, respectively) (Fig. 3c) and d)). The mean total Cd concentration exhibited a 42% decrease, from 0.38±0.09 mg kg^{-1} to 0.22±0.11 mg kg^{-1}. It is noteworthy that the Cd exceedance rate in the topsoil (based on China's national standard GB 15618-2018) decreased from 80% to 20%. Following the tilling process, the mean available Cd concentrations in the topsoil and subsoil layers were found to be as low as 0.032±0.035 mg kg^{-1} and 0.015±0.012 mg kg^{-1}, respectively. In summary, the implementation of deep plowing effectively reduced the concentrations of both Cd and available Cu/Cd in the topsoil.

Effect of Deep Plowing on Soil Fertility in Topsoil and Subsoil Layers

To assess the effects of deep plowing on soil fertility, we analyzed changes in key soil fertility indicators

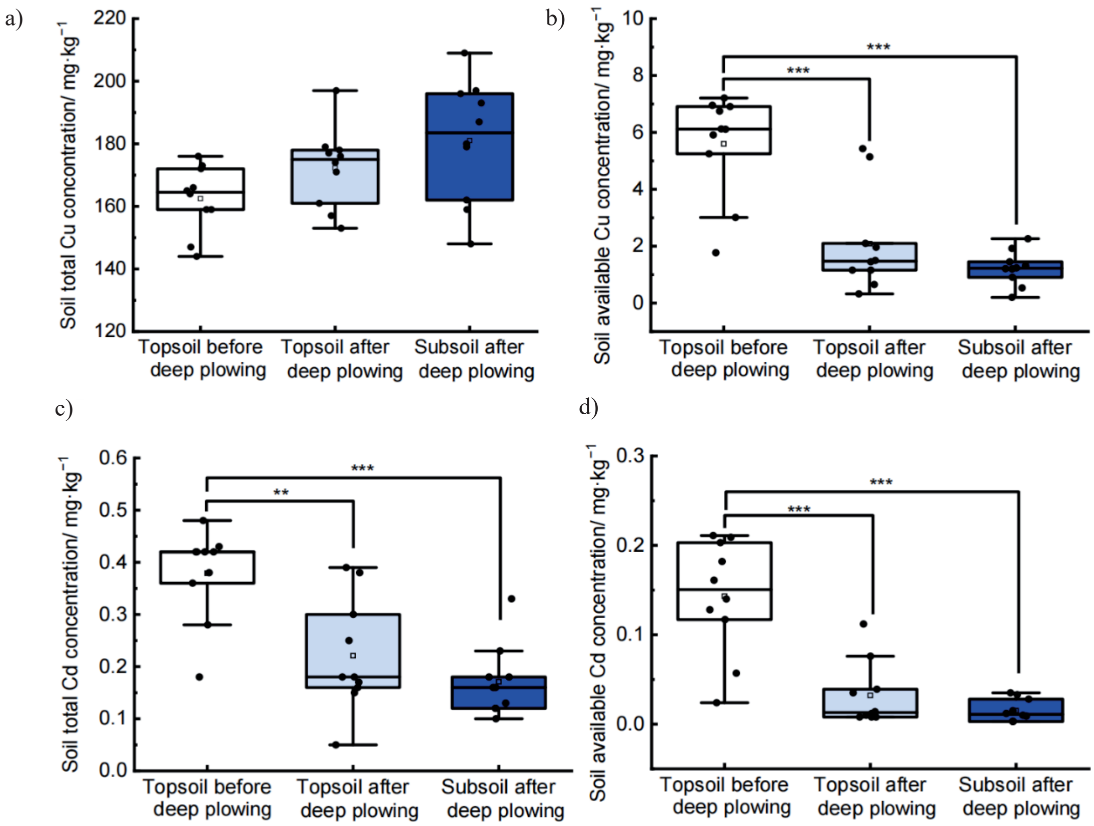

Fig. 3. Effect of deep plowing on soil a) total Cu, b) available Cu, c) total Cd, and d) available Cd concentrations. Values represent means of 10 sampling points (mean±SD). Asterisks (*, **, ***) indicate significant differences in soil heavy metal concentration before and after deep plowing at $p<0.05$, $p<0.01$, and $p<0.001$ levels, respectively.

following deep plowing treatment, along with soil nutrient classification (Fig. 4 and Table 2). The initial topsoil (0~20 cm) pH averaged 7.47±0.61 (in the neutral range). After deep plowing, the pH values decreased slightly to 6.66±0.81 in the topsoil and 6.74±0.93 in the subsoil (Fig. 4a)). However, these changes were not significant and remained within the neutral range. Most notably, deep plowing significantly reduced ($p<0.05$) topsoil organic matter (47%), total nitrogen (45%), and available nitrogen (36%) contents (Fig. 4(b-d)). Pre-tillage fertility levels were classified as rich (OM: 37.9±11.7 g·kg^{-1}; TN: 1.82±0.62 g·kg^{-1}; AN: 136.2 mg·kg^{-1}), whereas post-tillage levels declined to moderate or poor ranges (Table 2).

Compared to the pre-tillage topsoil, deep plowing did not significantly alter the concentrations of TP, AP, TK, or AK in the topsoil or subsoil (Fig. 4(e-h)). However, there was a decrease in AP and AK contents, though it was not statistically significant. Changes in the numerical values of soil fertility indicators resulted in changes to their grades (Table 2). Before deep plowing, the average AP content of this vegetable field was 10.7±5.3 mg·kg^{-1}, classifying it as moderate (10~20 mg·kg^{-1}) (Table 2). After deep plowing, the AP levels in the topsoil and subsoil decreased to the poor range (5-10 mg·kg^{-1}): 8.32±7.39 mg·kg^{-1} and 5.16±2.51 mg·kg^{-1}, respectively. Similarly, deep plowing reduced the AK concentration; the average

Table 2. Effect of deep plowing on soil fertility level.

Indexes[1]	Topsoil before DP	Topsoil after DP	Subsoil after DP
Organic matter	Rich	Medium	Poor
Total nitrogen	Rich	Medium	Poor
Available nitrogen	Rich	Poor	Poor
Available phosphorus	Medium	Poor	Poor
Available potassium	Very rich	Very rich	Very rich

Note: The grading standards for individual soil fertility indicators were determined based on the criteria of soil nutrient classification from China's Second National Soil Census. DP, deep plowing.

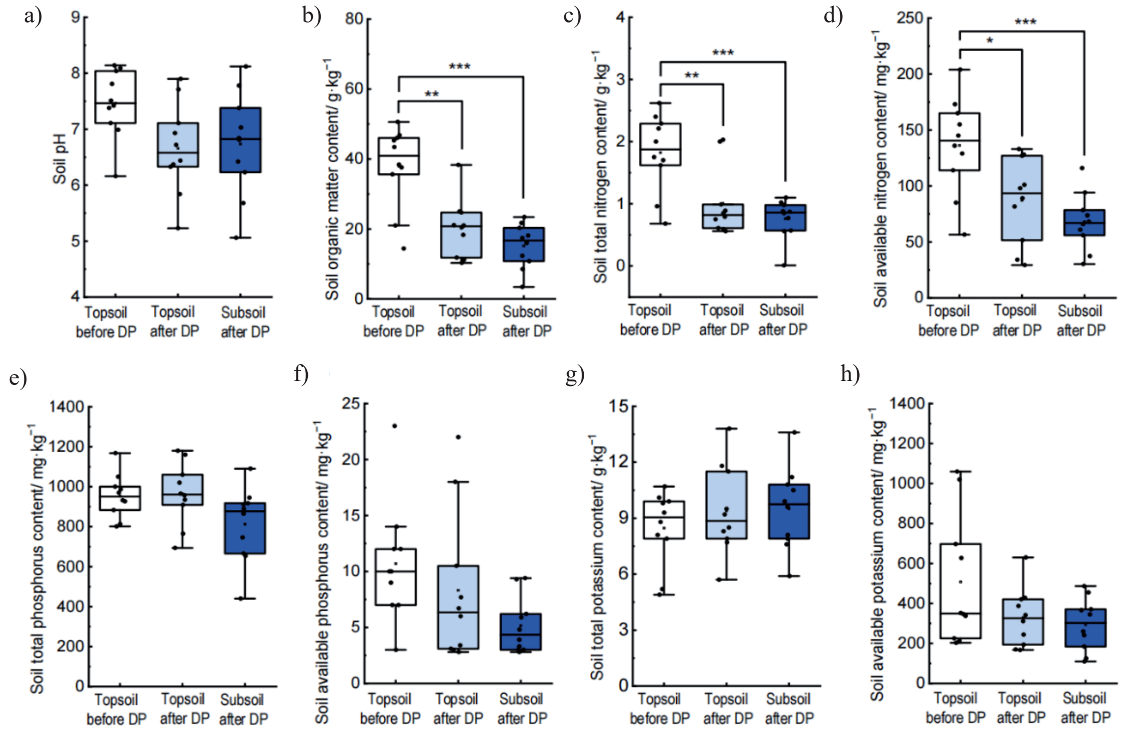

Fig. 4. Effect of deep plowing on soil fertility parameters. a) pH; b) organic matter; c) total nitrogen; d) available nitrogen; e) total phosphorus; f) available phosphorus; g) total potassium; h) available potassium. Values represent means of 10 sampling points (mean±SD). Asterisks (*, **, ***) denote significant differences in soil fertility indicators before and after deep plowing at p<0.05, p<0.01, and p<0.001 levels, respectively. DP, deep plowing.

AK concentration in the topsoil declined from 507±326 mg·kg^{-1} to 329±145 mg·kg^{-1}. However, the post-tillage AK levels remained in the "very rich" range. There were no significant differences in any soil fertility indicators between the topsoil and subsoil layers after deep plowing (Fig. 4(e-h)). Overall, deep plowing significantly reduced the topsoil OM, TN, and AN concentrations while homogenizing the basic physicochemical properties of the topsoil and subsoil layers.

Effect of Deep Plowing on Cu and Cd Contents of Local Vegetables

Six vegetables, which are common in this vegetable production base, were used to evaluate the effect of deep tillage on the accumulation of Cu and Cd in the edible parts of vegetables. The tested vegetables included three leafy vegetables (Chinese flowering cabbage, Chinese kale, and head lettuce), two fruit vegetables (tomato and pepper), and one legume vegetable (faba bean) (Table 3). The Cu and Cd contents in all tested vegetables were found to be below the maximum levels set by Chinese national food safety standards (GB 15199-94: Cu≤10 mg·kg^{-1} for vegetables and ≤20 mg·kg^{-1} for legumes; GB 2762-2022: Cd≤0.2 mg·kg^{-1} for leafy vegetables and ≤0.1 mg·kg^{-1} for legumes). However, it was obvious that deep plowing reduced the Cu and Cd contents in the edible parts of all six vegetables by 17% to 45%. Significant reductions (p<0.05) were observed, particularly in Chinese flowering cabbage and faba bean. Notably, the Cu and Cd contents in faba bean decreased markedly by 39% and 45%, respectively. These results demonstrate that deep tillage is an effective agronomic practice for reducing the bioavailability of Cu and Cd in this type of contaminated vegetable soil.

Discussion

In this study, we demonstrate that implementing 50 cm deep plowing in vegetable fields with low-level Cu and Cd contamination – particularly in plots exhibiting significant surface accumulation of heavy metals – constitutes an efficient and practical strategy for simultaneously achieving pollution remediation and maintaining agricultural productivity. This approach shows considerable potential for supporting sustainable land management in agricultural regions characterized by elevated geochemical background levels of heavy metals.

Surface Enrichment of Heavy Metals and the Rationale for Physical Remediation via Deep Plowing

The technique is particularly suitable for farmland soils where heavy metals have accumulated in

Table 3. Effect of deep plowing on Cu and Cd contents in the edible parts of vegetables.

Vegetable species	Cu content (mg·kg⁻¹)		Cd content (mg·kg⁻¹)	
	CK	DP	CK	DP
Chinese flowering cabbage	1.12±0.34	0.87±0.36*	0.042±0.013	0.023±0.015*
Chinese kale	0.95±0.41	0.83±0.27	0.031±0.014	0.019±0.006*
Head lettuce	0.85±0.21	0.71±0.37	0.012±0.004	0.010±0.003
Faba bean	0.64±0.21	0.39±0.14*	0.053±0.025	0.029±0.011*
Pepper	0.56±0.31	0.42±0.21	0.031±0.014	0.019±0.015
Tomato	0.51±0.23	0.46±0.19	0.016±0.015	0.012±0.006

Note: Values represent means of 6 samples (mean±SD). Asterisks (*) denote significant differences in Cu and Cd contents before and after deep plowing at $p<0.05$. DP, deep plowing.

the surface layer, as observed in the present case. Yunnan Province, situated in southwestern China, is characterized by naturally elevated background levels of heavy metals in soils. The widespread distribution of carbonate rocks in this region contributes to the presence of these toxic elements, which are primarily derived from parent rock materials [52, 53]. As a major center for non-ferrous metal mining and smelting in China, anthropogenic activities have further intensified the accumulation of heavy metals in local agricultural soils [37, 54]. Huang et al. reported that the geochemical benchmark value for Cu concentration in the Dianchi watershed soil in Yunnan Province (topsoil 0~20 cm) was 103.59±10.16 mg kg^{-1}, with a range of 74.25~138.95 mg kg^{-1}, slightly exceeding the Cu risk screening value of 100 mg kg^{-1} [36]. Furthermore, since 1980, Cu levels have shown a notable increasing trend and remained high between 1980 and 1995 (117.73±5.03 mg kg^{-1}). The karst terrain regions in southwestern China, including Yunnan, Guizhou, and Guangxi, all exhibited elevated background levels of heavy metals [55]. Additionally, it has been shown that the long-term application of manure could lead to heavy metal accumulation in surface soil (0-5 cm) of farmland [56]. Such contamination may inhibit vegetable growth and pose risks to the quality and safety of agricultural products [40]. Similar findings have been reported in previous studies. Kobierski et al. found that, compared with the reduced tillage system, full-inversion tillage significantly decreased the total Zn, Cu, Mn, and Fe content in arable sandy loam soils, while resulting in significantly higher plant-available Zn and Fe but lower total organic carbon [57]. In contrast, minimal tillage may lead to an increase in heavy metal content [58, 59]. Medvedeva et al. observed that, in Haplic Chernozem, minimal tillage resulted in a 26% increase in Zn content and a 34% increase in Cu content [59]. These observations support the rationale that areas characterized by surface enrichment of heavy metals are well suited for physical remediation via deep plowing, which effectively reduces metal availability in the upper soil layer.

Mechanisms of Reduced Heavy Metal Bioavailability

The dilution effect achieved through deep plowing successfully reduced the Cd exceedance rate from 80% to 20%, thereby bringing most of the field area below the risk screening values stipulated in GB 15618-2018. The significant reductions in topsoil Cd content (42%), available Cu (63%), and available Cd (78%) (Fig. 3) demonstrate that the dilution of highly contaminated topsoil with less contaminated subsoil effectively decreases the bioavailable pool of heavy metals. The effectiveness of deep tillage stems from the combined effects of "physical dilution" and the subsequent "secondary chemical processes" that it triggers [60]. While physical mixing rapidly reduces heavy metal concentrations in the surface layer, the newly formed soil environment initiates a series of complex chemical reactions that are crucial for the long-term stability and bioavailability of heavy metals. In particular, the iron-manganese oxides and layered silicate minerals introduced from the deep soil provide abundant new adsorption sites. Cu and Cd ions can be strongly immobilized on these mineral surfaces through specific adsorption, coprecipitation, or the formation of inner-sphere complexes, thereby reducing their concentration and mobility in the soil solution [61]. Moreover, following deep plowing, heavy metals may transform from more bioavailable forms – such as exchangeable and carbonate-bound fractions – into less bioavailable forms, including those bound to iron–manganese oxides and residual phases [62, 63]. This shift in speciation is critical to reducing heavy metal bioavailability and represents a more profound outcome than mere concentration dilution. The synergistic effect of these secondary chemical processes also explains why deep tillage causes little change in total copper content across soil depths yet markedly reduces available copper in both topsoil and subsoil layers (Fig. 3b)).

The corresponding reduction in Cu and Cd accumulation in vegetables following deep plowing further confirms that decreased bioavailability of these metals in soil results in lower uptake by vegetables. This outcome underscores the practical value of deep tillage as a soil risk mitigation strategy, as it allows agricultural production to continue safely without resorting to more costly or disruptive technologies. Although the initial Cu and Cd concentrations in the vegetables were below official safety limits, our approach is fundamentally preventive. By proactively reducing metal uptake, this method mitigates long-term dietary exposure and potential health risks for local consumers, thereby highlighting the importance of remediating contaminated farmland before it leads to the production of unsafe food.

Impacts on Soil Fertility

A direct consequence of deep tillage observed in our study was a significant reduction in the concentration of topsoil OM, TN, and AN (Fig. 4). This was an anticipated outcome, resulting from the dilution of nutrient-rich topsoil with infertile subsoil, and it represents a notable trade-off of this remediation technique. This decline in soil fertility translates to a temporary increase in fertilizer requirements to maintain crop yields in the seasons immediately following the intervention. Therefore, the applicability of deep soil mixing must be evaluated by weighing its primary benefit – rapid risk mitigation of heavy metals – against this tangible nutrient management cost.

Notwithstanding this fertility cost, the practice can be justified in contexts where the immediate reduction of metal bioavailability is the overriding priority. Furthermore, the formation of a homogeneous plow layer, as indicated by the uniform nutrient levels between the new topsoil and subsoil, simplifies subsequent fertilization management by eliminating sharp nutrient gradients. The stability of soil pH and P/K levels is also a positive indicator, suggesting that the process did not induce adverse chemical changes. Moreover, deep soil mixing can expand the shallow tillage layer, promote deeper root penetration, and enhance resource availability in the subsoil [64]. Importantly, this process simultaneously addresses the issue of soil compaction by breaking up dense soil layers and reducing bulk density, thereby improving soil porosity and creating a more favorable physical environment for root development. Ultimately, deep soil mixing should be implemented with the understanding that it is an initial remediation step that must be followed by vigilant nutrient management to restore soil productivity, making it a viable strategy primarily where the urgency of contamination control justifies the initial investment and short-term agronomic cost.

Comparative Advantages, Application Limitations, and Future Perspectives

Deep tillage aligns with the core objective of most *in-situ* remediation technologies: reducing the bioavailability and accessibility of toxic heavy metals [65]. Rather than removing pollutants, this approach redistributes them throughout a larger soil volume, thereby mitigating immediate risks while creating favorable conditions for long-term natural attenuation or phytoremediation processes. Deep soil mixing offers distinct advantages over other remediation strategies in specific scenarios. Unlike phytoremediation methods [66], which require multiple growing seasons to achieve significant results and often necessitate the suspension of agricultural production, deep plowing provides a rapid, one-time solution that allows immediate crop replanting. The primary investment involves the one-time cost of hiring a tractor and an operator for the deep plowing operation. In comparison to chemical immobilization techniques [67], which involve repeated amendment applications and pose risks of long-term secondary contamination or altered soil chemistry, deep soil mixing is a purely physical process with minimal long-term ecological uncertainty. Moreover, deep soil mixing represents a more cost-effective soil risk mitigation strategy than alternatives such as soil replacement or ex-situ washing, owing to its reliance on simpler mechanical equipment and operational procedures. This advantage makes it particularly suitable for implementation in regions with limited financial resources and for the remediation of farmland with mild, vertically distributed metal contamination.

However, this technique demonstrates certain limitations in its applicability. It is most effective in contexts where contamination is primarily confined to the topsoil layer, and the subsoil remains relatively uncontaminated. In cases involving deep leaching or subsoil pollution, the effectiveness of deep tillage is substantially diminished. Soil-specific properties at the subsurface must also be considered; for instance, deep plowing has proven efficient in soils with naturally dense layers (Inceptisols and Ultisols) [68]. The observed decline in soil organic matter and nitrogen content underscores a critical trade-off: gains in environmental safety may be accompanied by short-term reductions in soil fertility and may elevate the risk of nutrient leaching following fertilization, particularly in high-rainfall regions. Consequently, the implementation of deep soil mixing should be integrated with comprehensive nutrient management strategies, including the application of organic fertilizers or green manure, to rapidly restore soil organic carbon and nitrogen levels while ensuring long-term productivity. It has been shown that the combination of deep plowing with straw incorporation and balanced fertilization can further enhance soil organic carbon content, elevate N and P availability in middle and deep soil layers, improve subsoil physical properties, and ultimately increase crop yields [69-71]. This integrated approach is essential for achieving true agricultural sustainability – balancing remediation objectives with the preservation of soil ecosystem health. Future research should focus on several key areas: the long-term stability of remediation effects, the development of tailored nutrient management strategies to optimize soil health following deep soil mixing, and comprehensive economic assessments comparing this technique with alternative soil risk mitigation methods at regional scales.

Conclusions

In this study, a vegetable production base in Kunming was found to be mildly contaminated with Cu and Cd, with both total and available Cd and Cu exhibiting a surface accumulation pattern. Deep soil mixing was demonstrated to be an effective and practical remediation strategy for such contamination characteristics. This practice significantly reduced the concentrations of Cd, available Cu, and available Cd in the topsoil. Field experiments with local vegetable cultivation confirmed that deep plowing effectively lowered the Cu and Cd contents in the edible parts of crops. Furthermore, no significant differences in fertility indicators were detected between the topsoil and subsoil after deep plowing, indicating a homogenization of soil fertility throughout the plowed layer. These findings support the conclusion that deep soil mixing serves as a cost-effective soil risk mitigation strategy, enabling simultaneous crop production and soil remediation in lightly contaminated farmland. The study provides valuable practical insights for sustainable soil management in regions with similar pollution conditions.

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AI Usage Disclosure Statement

The authors used DeepSeek only for language polishing and stylistic refinement of this manuscript. No generative artificial intelligence tools were employed for data analysis, data interpretation, image or figure preparation, or the generation of original scientific content.

Conflict of Interest

The authors declare no conflict of interest.

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