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Cadmium Accumulation and Immobilization by *Artemisia selengensis* under Different Compound Amendments in Cadmium-Contaminated Soil

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Abstract: Cadmium (Cd) contamination is a global environmental challenge that threatens human food security. Lime combined with five different organic materials (rape seed cake, mushroom residue, straw, sawdust, and corn cobs) (LOM) at application ratios of 1:1 and lime sawdust combined with nitro-compound fertilizer ($Ca(NO_3)_2 \cdot 4H_2O$, KH_2PO_4, KNO_3) (LSF) at different application rates were applied to Cd-contaminated soil. The present study investigates the effects of these organic–inorganic compound amendments on Cd bioavailability in soil, and Cd uptake and accumulation by edible *Artemisia selengensis* parts. *A. selengensis* was cultivated for three consecutive seasons in Cd-contaminated soil. LOM and LSF treatments obviously reduced the uptake and accumulation of Cd. Compared with the control soil, contents of Cd in edible parts of *A. selengensis* decreased by 19.26–33.33% and 26.67–32.78% in the first season, 18.60–32.79% and 18.37–32.79% in the second season, and 20.45–40.68% and 34.32–37.27% in the third season, respectively. The addition of Lime + Mushroom Residue and 70% Nitro-compound Fertilizer + Lime + Sawdust most significantly reduced Cd concentrations in the edible parts of the third *A. selengensis* season. LOM and LSF application increased soil pH and improved soil fertility, including available nitrogen, available phosphorus, available potassium, organic matter, and cation exchange capacity. Lime + Mushroom Residue improved plant yield the most. In addition, Lime + Mushroom Residue and 70% Nitro-compound Fertilizer + Lime + Sawdust had the lowest Cd accumulation and health risk indices, respectively. In conclusion, the Lime + Mushroom Residue and 70% Nitro-compound Fertilizer + Lime + Sawdust amendments significantly reduced health risks, enhanced *A. selengensis* growth, and promoted sustainable development of arable land under Cd-contaminated soil remediation.

Keywords: soil Cd; vegetables; health risk assessment; safety production; soil remediation

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1. Introduction

Heavy metal contamination of agricultural soil, which is associated with rapid industrial development and unprecedented natural ecosystem degradation under population explosion, is considered a major threat to food security and ecological health [1,2]. Cadmium (Cd) is considered one of the most toxic elements, with long-term concealment and non-degradable characteristics [3,4]. Anthropogenic activities, such as sewage irrigation, excessive fertilization, mining, and metal smelting, are the major sources of Cd released into the soil, leading to soil pollution and deterioration [5]. Cd is highly mobile, and Cd in the food chain has contributed significantly to the toxicity of food crops [6]. Long-term exposure to Cd causes diabetes, tubular impairment, cancer, or hypertension [7]. In addition, Cd in contaminated soil is readily absorbed by plant roots, particularly leafy vegetables, and then transported to the aboveground parts, with critical effects on morphology and growth rate [8–10]. Cd pollution, therefore, is a threat to food security, by decreasing food production and quality, in addition to posing health risks to humans, even at low soil Cd levels [11,12]. Consequently, strategies for reducing Cd concentrations in vegetables and agro-ecosystems are urgently required for agri-environmental sustainability and food safety.

Numerous soil remediation measures have been established for heavy-metal-contaminated agricultural soils, including physical, chemical, and biological methods, such as soil replacement [13], electrokinetic remediation [14], inorganic amendments (alkaline materials, phosphates, and clay minerals) [15–17], organic amendments (biosolid compost, biochar, and manures) [18]. Chemical remediation reduces Cd content principally by precipitation or cation exchange, sorption, complexation, and redox reactions, which result in the transport and transformation of contaminants [19]. Amendments could decrease exchangeable Cd concentrations by reducing soil bioavailability fractions and ecotoxicity, which directly mitigate heavy metal toxicity [20].

Combined amendments could enhance metal immobilization capacity and achieve better outcomes than the application of a single amendment [21]. Organic and inorganic amendments are cost effective and environmentally friendly, in addition to having soil stabilization properties, considering their high absorption capacity and physical structure following amendment to contaminated soil [22]. Organic amendments not only improve soil fertility correlated with organic matter addition, they also increase the surface charge, which facilitates Cd phytotoxicity alleviation [23]. Lime is an alkaline amendment that can release a large number of OH- ions, which increase soil pH and promote the concomitant sorption of Cd by contributing to the precipitation of Cd in soil, can be applied as a co-amendment [24,25]. Inorganic fertilizers influence Cd bioavailability in plants significantly and decrease Cd translocation from the root to the shoot [26]. In crop production, such organic–inorganic compound amendments are suitable from a technical point of view; however, their large-scale soil remediation effects are not clear.

Artemisia selengensis (*A. selengensis*), is a perennial herb in the family Asteraceae that grows in shallow aquatic and terrestrial environments, with the edible parts being tender stems and leaves. *A. selengensis* contains various nutrients, including calcium, iron, zinc, and vitamins, 17 amino acids, and has extensive medicinal applications [27].

In the present study, a field experiment was carried out in Cd-contaminated soil in Nanjing City, Jiangsu province. The organic–inorganic combined amendments lime with five organic materials (rape seed cake, mushroom residue, straw, sawdust, and corn cobs) (LOM) at an application ratio of 1:1, and different application rates of lime, sawdust combined application with nitro-compound fertilizer ($Ca(NO_3)_2 \cdot 4H_2O$, KH_2PO_4, KNO_3) (LSF) were selected to remediate Cd-contaminated soil. We assumed that organic–inorganic compound amendments would have better effects on decreasing Cd concentrations in soil than a single amendment. Therefore, we applied these organic–inorganic compound amendments to soil and then cultivated *A. selengensis* on it. The effects of compound amendments on Cd uptake by the edible parts of *A. selengensis* across three seasons, *A. selengensis* yield, soil pH and nutrient, and Cd availability content in soil were explored. The aims of the present study were to: (1) investigate the effectiveness of organic–inorganic compound amendments on reducing Cd availability in soil; (2) determine the impacts of organic–inorganic amendments on Cd accumulation in the edible parts of *A. selengensis* and yield; and (3) assess the human health risk, achieving Cd-contaminated soil remediation and safe production of *A. selengensis*.

2. Materials and Methods

2.1. Soil Characterization

The study area, Baguazhou Island, is located in a suburb of northeastern Nanjing City (32°19′11″ N, 11°80′39″ E), Jiangsu province, China. The region has a subtropical monsoon climate with an annual average precipitation of 1000–1100 mm and a temperature of 15.4 °C. The soil texture is dominated by paddy soils (Fe-leachi-Stagnic Anthrosols, based on USA Soil Taxonomy) with a low quantity of calcareous alluvial soils (Ochri-Aquic Cambosols, based on USA Soil Taxonomy), originating from the sediment of the Yangtze

River. The island is mainly used to cultivate special vegetables and is known as "The land of *Artemisia selengensis*". Baguazhou island is in the lower reaches of the Yangtze River with numerous large enterprises and factories located along the two sides. On account of its unique geographical location, Cd contamination in soil has mainly been caused by increasing human activities. In the present study, two plots of agricultural soils affected by Cd contamination were selected. The basic properties of the two tested area soils are listed in Table 1.

Table 1. Characteristics in soil of LOM and LSF experiment areas.

Treatments	pH	OM (g kg^{-1})	CEC (cMol kg^{-1})	TN (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	Total Cd (mg kg^{-1})	Available Cd (mg kg^{-1})
LOM	5.75	26.99	12.52	2.35	104.40	152.23	174.40	0.30	0.08
LSF	5.54	26.31	14.52	2.11	94.53	110.81	162.40	0.30	0.09

TN: Total nitrogen; AN: Available nitrogen; AP: Available phosphorus; AK: Available potassium; OM: Organic matter; CEC: Cation exchange capacity.

2.2. Experimental Design and Treatments

In the present study, the effects of different combinations of amendments, including LOM (lime combined with rape seed cake, mushroom residue, straw, sawdust and corn cobs, respectively) and LSF (different application rates of lime and sawdust combined with nitro-compound fertilizer), applied to Cd-contaminated soil were screened by comparing their immobilization effects and effects on *A. selengensis* Cd accumulation. The study was carried out using a completely randomized block design with one study area, with each treatment having three replicates. The experimental plant *A. selengensis* was planted for three continuous seasons. In the two field experiments, five treatments consisted of lime combined with five different organic materials, and six treatments consisted of six different application rates of lime and sawdust combined with nitro-compound fertilizer. Their abbreviation and major application rates are listed in Tables 2 and 3. In addition, soil with no amendment was set as the unamended control (CK), and the two experiments shared the same CK.

Table 2. Experimental design and application amount of LOM.

Treatments	Abbreviation	Application Rates (kg plot^{-1})		
		Inorganic Fertilizers	Lime	Organic Materials
Control	CK	17.2	0	0
Lime + Rape Seed Cake	L + RSC	17.2	17.2	17.2
Lime + Mushroom Residue	L + MR	17.2	17.2	17.2
Lime + Straw	L + S	17.2	17.2	17.2
Lime + Sawdust	L + SD	17.2	17.2	17.2
Lime + Corn Cobs	L + CC	17.2	17.2	17.2

LOM (lime, five organic materials: rape seed cake, mushroom residue, straw, sawdust, corn cobs) were applied as basal fertilizer before *A. selengensis* was transplanted into the plots. Based on NAU Lime Calculator, the CaO application rate is 0.375 kg m^2 and the lime combined with organic materials application at ratios of 1:1.

The study was conducted from August 2021 to May 2022. The experimental design included a total of 36 sampling plots across the two sites. Each plot measured 11.5 m × 4 m, and was divided with a 0.5 m wide protection row. Each plot had a separate 30 cm inlet and 30 cm outlet for irrigation and drainage, respectively. In August 2020, amendments were evenly applied to the corresponding field plots and mixed with the soil mechanically and left to equilibrate for 10 days. The recommended N-P_2O_5-K_2O (16-16-16) compound fertilizer was applied as additional fertilizer in one season when *A. selengensis* was sprouting to meet the basic plant growth demands. After two weeks, the first *A. selengensis* shoots were transplanted directly into the corresponding plots in the fourth week of August, and the last season was harvested in the third week of April. In the middle of the second season, greenhouses were installed to protect plants from exposure to freezing stress. *A. selengensis* shoots were obtained from the previous season post harvest, and mature individuals with incomplete lignification were selected. Planting density and agronomic management were consistent with local agricultural practices.

Table 3. Experimental design and application amount of LSF.

Treatments	Abbreviation	Application Rates (kg plot^{-1})			
		Inorganic Fertilizers	Nitro-Compound Fertilizer	Lime	Sawdust
Control	CK	17.2	0	0	0
Nitro-compound Fertilizer	F	17.2	17.2	17.2	0
Nitro-compound Fertilizer + Lime	F + L	17.2	17.2	17.2	0
80%Nitro-compound Fertilizer + Sawdust	80%F + SD	20.6	13.8	0	17.2
80%Nitro-compound Fertilizer + Lime + Sawdust	80%F + L + SD	20.6	13.8	17.2	17.2
70%Nitro-compound Fertilizer + Sawdust	70%F + SD	22.4	12.1	0	17.2
70%Nitro-compound Fertilizer + Lime + Sawdust	70%F + L + SD	22.4	12.1	17.2	17.2

Lime and sawdust were applied as basal fertilizer before *A. selengensis* was transplanted into the plots. Nitro-compound fertilizer was applied as additional fertilizer after *A. selengensis* was transplanted into the plots. The composition of the compound fertilizer was calcium nitrate tetrahydrate, potassium dihydrogen phosphate, and potassium nitrate ($Ca(NO_3)_2{\cdot}4H_2O$, KH_2PO_4, KNO_3). 80% Nitro-compound fertilizer and 70% Nitro-compound fertilizer indicates substitution with 20% and 30% N-P_2O_5-K_2O (16-16-16), respectively.

2.3. Soil and Plant Sampling and Analysis

Composite soil samples were collected from each plot before amendment application to analyze the background values. The second round of soil sampling was performed after the edible *A. selengensis* parts were uprooted at maturity at the end of the third season, and corresponding soil samples were obtained near the root. Three soil subsamples were randomly collected in the same plot and combined to obtain a representative sample. Three seasons of *A. selengensis* samples were harvested in October 2021, December 2021, and April 2022. The fresh vegetable samples were collected in clean polyethylene valve bags, transported to the laboratory by cold chain, and divided into edible parts (stems and leaves) and non-edible parts (roots). The edible parts of vegetable samples were washed with tap water three times and deionized water once to remove mud, dried in an oven to constant weight, and then ground for use in chemical analysis.

The soil was sampled from the surface layer (0–20 cm) in the study area. Soil samples were air-dried at room temperature (20 ± 5 °C), and then stones and other debris were removed, followed by sieving with a 2.0 mm nylon sieve, for use in the estimation of soil parameters. Portions of soil samples were ground in a mortar and sieved with a 0.149 mm nylon sieve to measure the following indicators.

Soil pH was measured using a pH glass electrode with 1:2.5 (weight/volume ratio) distilled water extraction. Available phosphorus (AP) was measured according to the Olsen method [28]. Available potassium (AK) was extracted for 30 min with 1:10 (soil/solution ration of 1:10) NH_4OAc and then analyzed using a flame spectrophotometer (BWB-XP, England) [29]. Available nitrogen (AN) and organic matter (OM) contents were determined using the alkali-hydrolysis and diffusion method and potassium dichromate oxidation with low-temperature external heating, respectively, as described in [30]. Cation Exchange Capacity (CEC) was extracted in 1M NH_4OAc and then measured using flame atomic absorption spectroscopy [31]. The total Cd concentration in soil was determined by weighing 0.2 g of digesting soil with a mixed HF-$HClO_4$-HNO_3 (1:1:5) solution, and placing it in a polytetrafluoroethylene crucible [32]. The available Cd content in soil was determined by weighing 8 g of soil and using 20 mL of 0.1M $CaCl_2$ in a 25 mL centrifuge tube according to Esnaola [33].

To measure the Cd content in the edible *A. selengensis* parts, the plant samples were crushed using a high-speed grinder and then sieved with a 0.15 mm nylon sieve, and Cd content was analyzed using the method of Bao [32]. The plant samples (0.2 g) were treated with a mixed HNO_3-$HClO_4$ (2:1) solution and digested in a microwave digestion tube at 170 °C. The Cd concentration in the digested samples was subjected to inductively coupled plasma–mass spectrometry (ICP-MS).

2.4. Cadmium Migration and Transformation Analysis

Cd bioavailability (*BA*) was used to evaluate the impact of Cd pollution in soil [34], which was expressed based on the ratio of soil-available Cd concentration (mg kg^{-1}) to total Cd concentration (mg kg^{-1}), as follows:

$$BA = \frac{C_{available}}{C_{total}}$$

Cd Bioconcentration Factor (*BCF*) was calculated to evaluate soil Cd migration and transformation abilities in plant edible parts, which are key indicators for assessing soil contamination health risks and soil environmental quality. The relationship is expressed as follows:

$$BCF = \frac{M_P}{M_S}$$

where M_P is Cd concentration in edible parts of *A. selengensis* (mg kg^{-1}), whereas M_S is the total Cd concentration in soil (mg kg^{-1}).

2.5. Human Health Risk Assessment

The Target Hazard Quotient (*THQ*) index was established by the United States Environmental Protection Agency [35] to facilitate the evaluation of the potential health risks of consuming food products contaminated by toxic elements. If $THQ < 1$, there is no obvious health risk for individuals who are exposed to pollutants; conversely, the health risk exists. The equation can be expressed as follows, according to Wang [36]:

$$THQ = \frac{EF \times ED \times IR \times C_m}{B_W \times AT \times RfD \times 100}$$

where *EF* is exposure frequency (365 d $year^{-1}$); *ED* is exposure duration (70 years); *IR* is daily vegetable consumption (0.2762 kg $person^{-1}$ d^{-1} of vegetables); C_m is Cd concentration in vegetable edible parts; B_W is average body weight (60.6 kg $person^{-1}$); *AT* is the average duration of exposure to non-carcinogens (365 d $year^{-1}$ × number of exposure years; the present study assumed 70 years); and *RfD* is the reference dose. According to USEPA, the *RfD* value for Cd is 0.001 mg kg^{-1}.

Health Risk Index (*HRI*) estimates the risk level of human exposure to Cd following consumption of contaminated vegetables, according to Rehman [37]. The equation can be expressed as follows:

$$HRI = \frac{DIM}{RfD}$$

The above-mentioned daily intake of Cd (*DIM*) was estimated as described:

$$DIM = \frac{C_m \times C \times IR}{B_W}$$

C is the setting value of 0.085.

2.6. Statistical Analysis

In the present study, IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, USA), Origin 2022b (OriginLab, Northampton, MA, USA), and MS Excel 2016 (Microsoft Corp., Redmond, WA, USA) were used for data processing and statistical analysis. All analyses were performed in quintuplicate. The experimental data were subjected to one-way Analysis of Variance (ANOVA) and Duncan's test at $p < 0.05$ in IBM SPSS Statistics 26 (IBM Corp.) to determine the significant differences among different treatments. Graphical and tabular data were presented using Origin 2022b (OriginLab) and MS Excel 2016 (Microsoft Corp.). All data are presented as mean ± standard error.

3. Results

3.1. Soil pH and Soil Nutrient Trends

Figures 1 and 2 illustrate the pH, OM, CEC, AN, AP, and AK trends among different treatments in the LOM and LSF treatment plots after harvesting in the third season. The effect of organic amendments on soil pH can be observed in Figure 1a. Compared with levels in the CK, all treatments resulted in an increase in soil pH. Soil amendment with L + MR, L + S, L + SD, and L + CC significantly increased the soil pH ($p < 0.05$), by 14.47%, 18.57%, 15.03%, and 12.30, respectively. In addition, L + RSC amendment increased pH by 9.01%, although the increase was not significant ($p > 0.05$) when compared with the level in the CK. In conclusion, lime combined with organic materials can improve the soil pH, with L + S being the most effective in improving the pH. Among the LSF treatments, when compared with the control, all six treatments increased soil pH, by 9.33% (F), 15.94% (F + L), 14.16% (80%F + SD), 21.21% (80%F + L + SD), 14.60% (70%F + SD), 19.11% (70%F + L + SD), when compared with the control (Figure 2a), and all increases were significant ($p < 0.05$). The addition of LSF treatments all significantly ($p < 0.05$) increased soil pH, with 80%F + L + SD having the best results.

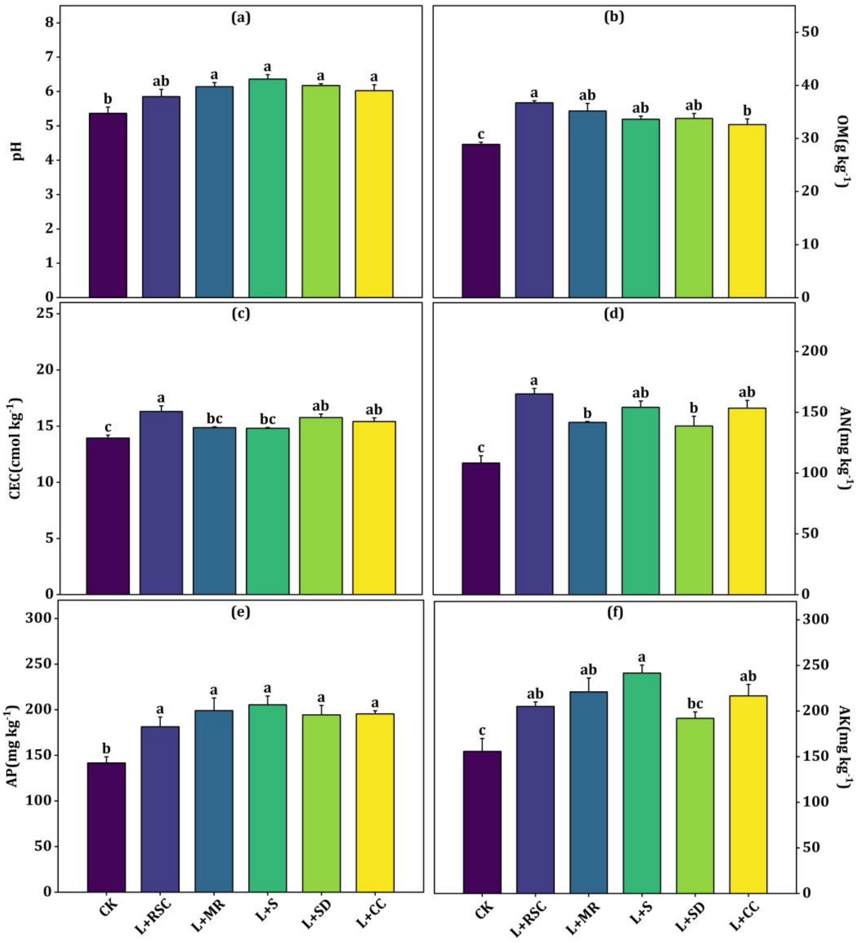

Figure 1. Effect of LOM on soil pH (**a**), OM (**b**), CEC (**c**), AN (**d**), AP (**e**), and AK (**f**) of *A. selengensis*. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$).

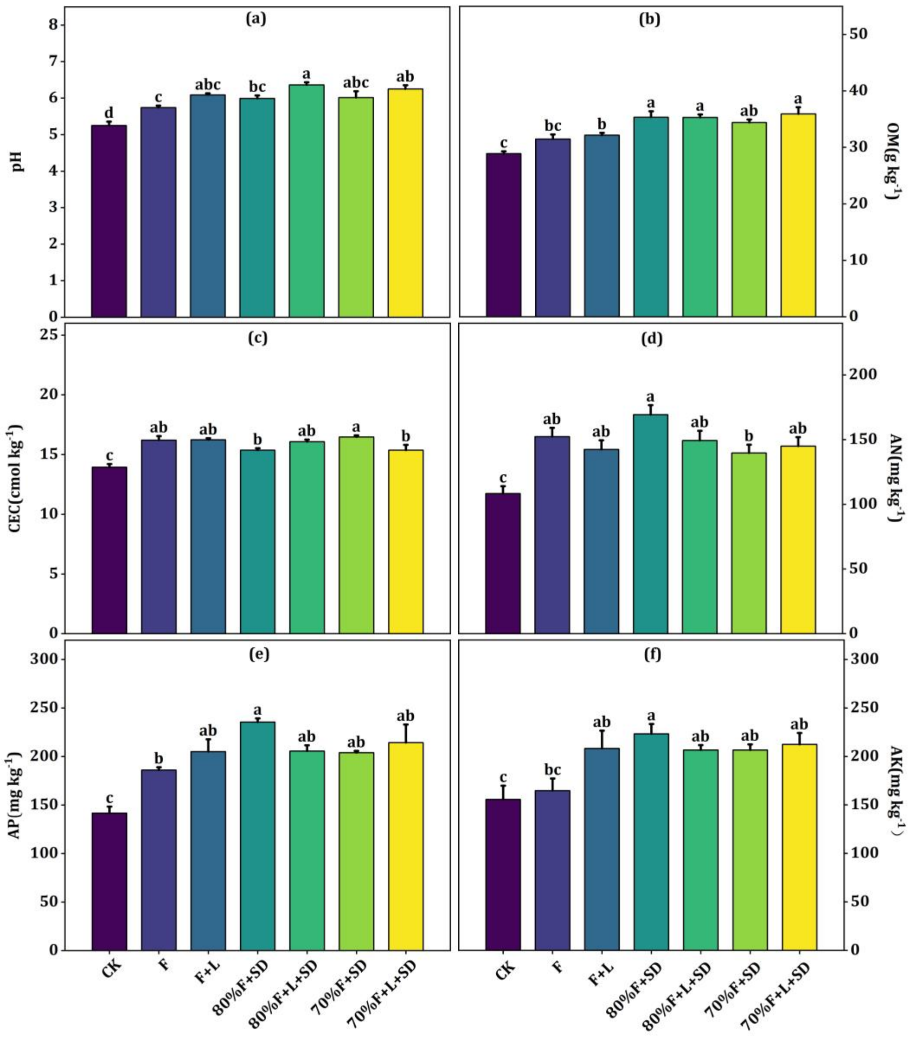

Figure 2. Effect of LSF on soil pH (**a**), OM (**b**), CEC (**c**), AN (**d**), AP (**e**), and AK (**f**) of *A. selengensis*. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$).

In addition, LOM in *A. selengensis* enhanced soil AN (Figure 1d), AP (Figure 1e), and AK (Figure 1f).

There were significant differences ($p < 0.05$) between different treatments among the amendments. All five LOM treatments, including L + RSC, L + MR, L + S, L + SD, and L + CC increased AN by 52.35%, 30.81%, 42.20%, 28.04%, and 41.58%, respectively, when compared with the control treatment (Figure 1d). The L + RSC treatment performs best in increasing soil AN content among the five treatments. Similarly, all treatments increased AP in the range of 28.00–44.94%, with the highest increase observed under L + S at 44.94%, followed by under L + MR (40.47%), L + CC (37.88%), L + SD (37.18%), and L + RSC (28.00%) (Figure 1e). In addition, AK increased significantly ($p < 0.05$), by 55.25%, 41.97%, 39.19%, and 31.69%, under the L + S, L + MR, L + CC, and L + RSC treatments, respectively, and the L + SD increased AK by approximately 23.34%, although the difference was not significant ($p > 0.05$) (Figure 1f). Overall, the AN, AP, and AK contents in amended *A. selengensis* soil increased obviously, by 28.04–52.35%, 28.00–44.94%, and 23.34–55.25%, respectively, when compared with the levels in the unamended soil.

Figure 2 illustrates that the application of LSF treatments induced diverse effects with regard to AN (Figure 2d), AP (Figure 2e), and AK (Figure 2f) contents under different treatments. Specifically, compared with the unamended soil, all the treatments increased AN, AP, and AK contents. The AN content increased significantly ($p < 0.05$) under all treatments, with increases ranging from 28.96–56.36%, and the increasing order of treatments was 80%F + SD > F > 80%F + L + SD > 70%F + L + SD > F+ L > 70%F + SD (Figure 2d). In addition, AP and AK trends were similar under different treatments. AP content significantly ($p < 0.05$) increased by 31.29–66.24% under the different treatments compared to the control. For AK, the addition of 80%F + SD significantly ($p < 0.05$) increased AK, while F had no significant ($p > 0.05$) effect on AK content. Overall, the highest AN, AP, and AK soil contents were observed under the 80%F + SD treatment, which represented significant increases of 56.36%, 66.24%, and 43.47% ($p < 0.05$), respectively, when compared with the CK.

All LOM treatments increased soil OM significantly ($p < 0.05$) (Figure 1b). Furthermore, the L + RSC treatment increased OM by 27.10%, and the corresponding values under L + MR, L + SD, L + S, and L + CC were 21.68%, 16.84%, 16.38%, and 12.92%, respectively. OM contents in soil were significantly higher following treatment with LSF than in the control treatment (Figure 2b). The OM content increased significantly ($p < 0.05$) with all treatments except F, while the 70%F + L + SD treatment increased OM markedly by 24.34%.

The L + RSC treatment had the greatest effect on CEC, improving it by 16.99% in the soil in the study area. The LOM treatments increased CEC by 6.22–16.99% when compared with the values in the untreated soil, but there was no significant ($p > 0.05$) difference under the L + MR and L + S treatments (Figure 1c). Compared with that in CK, soil CEC increased significantly ($p < 0.05$) following LSF amendment, and the maximum CEC was observed under the 70%F + SD treatment, which represented an 18.18% increase when compared with that in the CK (Figure 2c).

3.2. Effect on *A. selengensis* Yield

The *A. selengensis* plants treated with LOM and LSF treatments grew normally, and their yields are illustrated in Figures 3 and 4 compared with the control soil; all LOM treatments increased yield significantly ($p < 0.05$), and the L + MR treatment increased the yield the most, by 15.76%. The corresponding values for L + RSC, L + S, L + SD, and L + CC were 11.17%, 12.68%, 11.57%, and 12.71%, respectively (Figure 3).

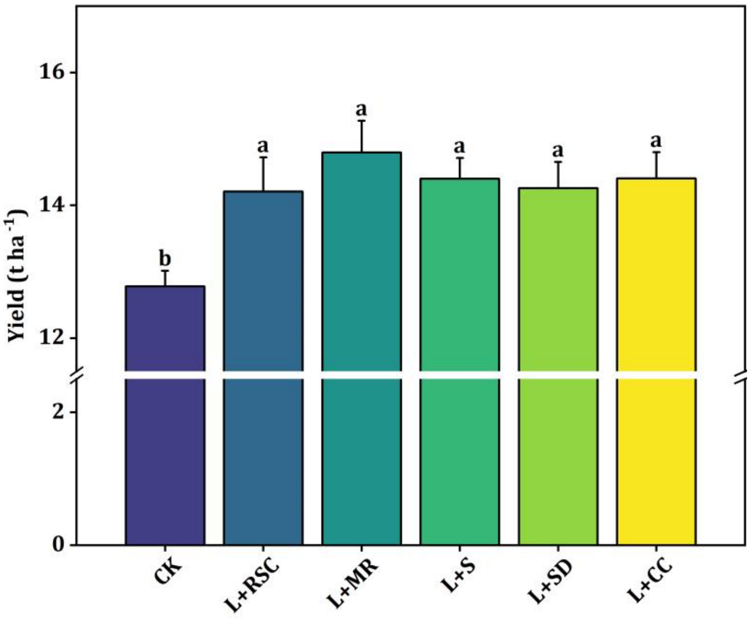

Figure 3. Effect of LOM on yield of *A. selengensis*. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$).

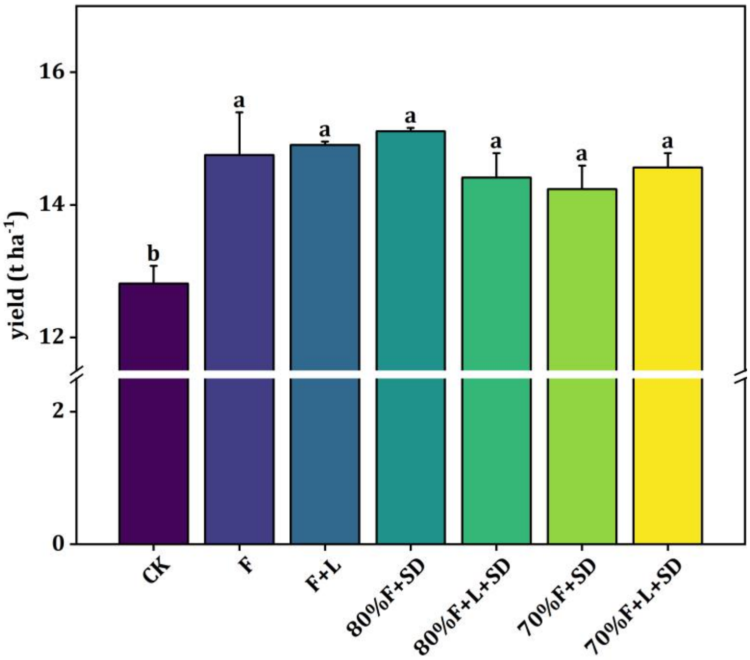

Figure 4. Effect of LOM on yield of *A. selengensis*. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$).

Inorganic compound fertilizers also increased *A. salengensis* yield significantly ($p < 0.05$) (Figure 4), with the greatest increase observed under 80%F + SD, at 17.94%. The corresponding increases under F, F + L, 80%F + L + SD, 70%F + SD, and 70%F + L + SD were 15.12%, 16.31%, 12.47%, 11.11%, and 13.65%, respectively.

3.3. Cd Absorption by Edible Parts of A. selengensis over Three Seasons

The Cd concentrations in the edible parts of *A. selengensis* across three seasons under LOM and LSF in the study area are presented in Figures 5 and 6, respectively. Compared with the CK, all LOM treatment applications significantly decreased Cd contents in the three seasons ($p < 0.05$). In the first season, the minimum Cd content was observed under L + MR, which was significantly lower than that in the CK ($p < 0.05$), by 30.93%. In the second season, Cd content in *A. selengensis* was the lowest under the L + SD treatment, although there were no significant ($p > 0.05$) differences between treatments. In the third season, the lowest Cd content was observed under the L + MR treatment, which was a 40.68% decrease when compared with that for the untreated soil, followed by those for the L + SD, L + S, L + CC, and L + RSC treatments. All the decreases under all the LOM treatments were significant ($p < 0.05$) for Cd content in the edible parts of the three seasons of *A. selengensis*.

The red dashed line in Figure 5 represents the Cd standard limit according to the Chinese Quality Standard for Food Safety—Limits of Contaminants in Food. According to local dietary habits, the stem is the edible part of *A. selengensis.* The Cd concentration of stems was 0.1 mg kg^{-1}. In all LOM treatments excluding L + RSC, the Cd contents in the edible parts of *A. selengensis* were below the standard limit of 100 μg kg^{-1} after the third-season harvest.

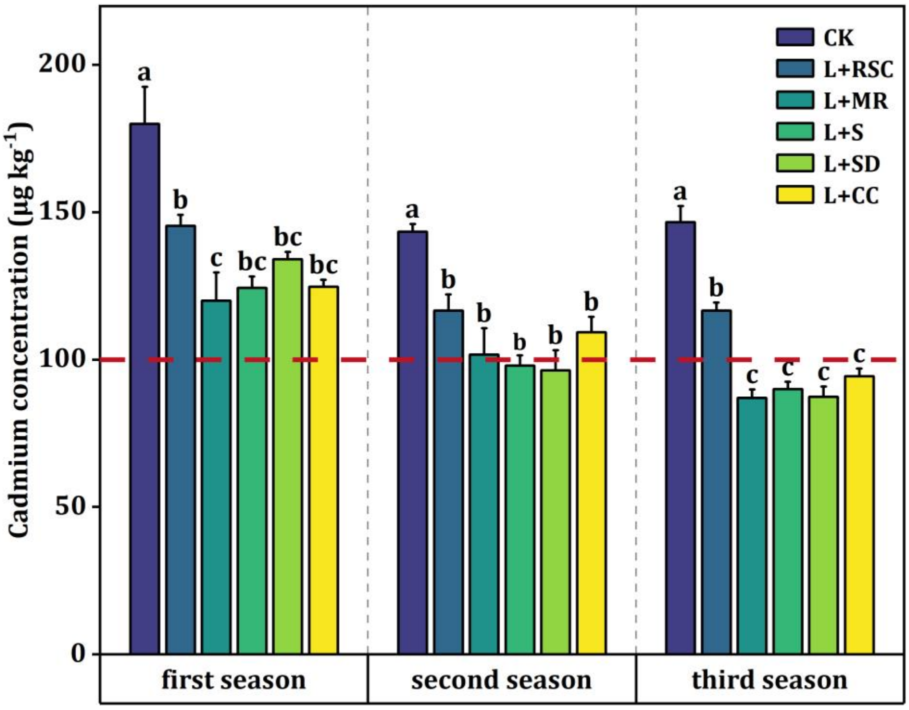

Figure 5. Effect of LOM on Cadmium concentration in edible parts of *A. selengensis* over three seasons. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$). The red dashed line indicates the standard limit of 0.1 mg kg^{-1} according to the Chinese Quality Standard for Food Safety-Limits of Contaminants in Food.

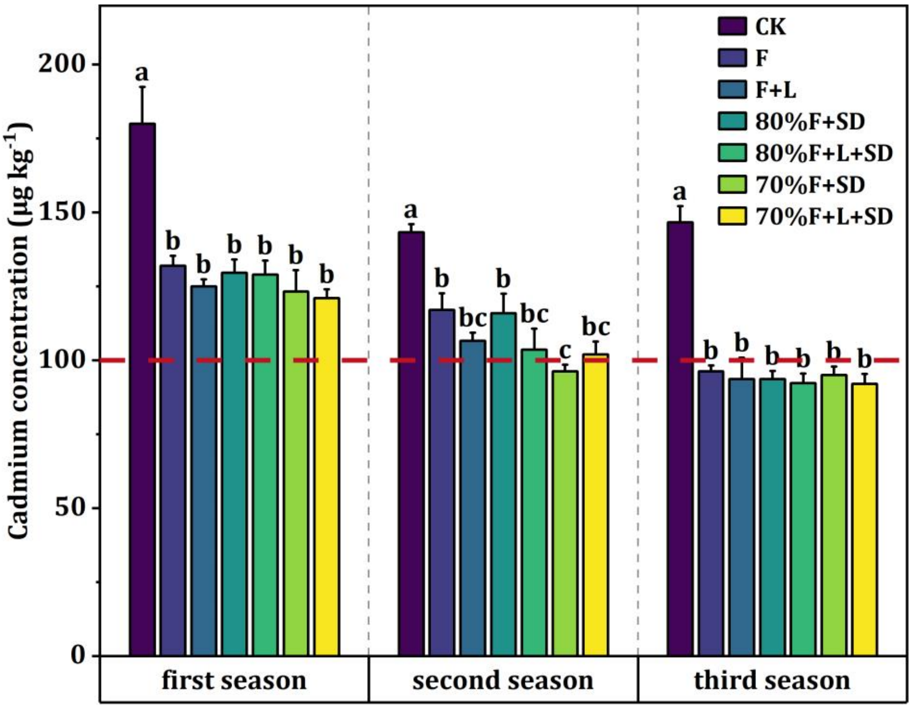

Figure 6. Effect of inorganic compound fertilizers on Cadmium concentration in edible parts of *A. selengensis* over three seasons. All values are means of three replicates with error bars indicating the standard error. Different lowercase letters show significant variability among treatments ($p < 0.05$). The red dashed line indicates the standard limit of 0.1 mg kg^{-1} according to the Chinese Quality Standard for Food Safety—Limits of Contaminants in Food.

As illustrated in Figure 6, Cd concentration was affected significantly ($p < 0.05$) by different application rates of LSF. The F, F + L, 80%F + SD, 80%F + L+SD, 70%F + SD, and 70%F + L+SD treatments influenced Cd concentrations in the edible parts significantly ($p < 0.05$), decreasing it by 26.67%, 30.56%, 27.96%, 28.33%, 31.48%, and 32.78%, respectively, when compared with the control, in the first season. There was no significant difference in Cd concentration in the edible part of the first season of *A. selengensis* between treatments. The 70%F + SD treatment reduced Cd content the most during the second season, at 32.78%. The F and 80%F + SD treatments were significantly ($p < 0.05$) different from 70%F + SD, however, decreasing Cd concentration by 18.37% and 19.07% more, respectively. In the third season, all six treatments decreased Cd in the edible parts significantly ($p < 0.05$), by 34.32–37.27%, when compared with CK, with no significant differences among the treatments. The greatest reductions in Cd were observed under the 70%F + L + SD, 70%F + SD, and 70%F + L + SD treatments, which were 32.78%, 32.79%, and 37.27% lower, respectively, than that in the CK. Cd contents in the edible parts of *A. selengensis* in all the treatments were below the standard limit in the third season under the different LSF treatments (Figure 6).

3.4. $CaCl_2$ Extractable Cd and Transfer Process in the Soil

There was a significant ($p < 0.05$) downward trend in soil available Cd concentration under different LOM treatments when compared with the control (Table 4). Among the LOM treatments, the greatest decrease was observed under the L + MR treatment (55.89%), and the corresponding reductions under L + SD, L + S, L + RSC, and L + CC were 48.84, 37.80, 30.71, and 21.26%, respectively.

Table 4. Effect of LOM on soil available Cd concentration, Cd bioconcentration factor (BCF), and Cd bioavailability (BA) of *A. selengensis*, daily intake of Cd (DIM), Cd-associated health risk index (HRI), and the target hazard quotient (THQ) related to *A. selengensis* cultivated on Cd-contaminated soil. All values are means of three replicates ± standard errors. Different lowercase letters indicate significant variability among treatments ($p < 0.05$).

LOM Treatments	Available Cd (μg kg^{-1})	BCF	BA	DIM	HRI	THQ
CK	42.330 ± 1.186 a	0.543 ± 0.036 a	0.154 ± 0.008 a	0.00000568 a	0.00568 a	0.668
L + RSC	29.330 ± 2.841 b	0.500 ± 0.010 a	0.125 ± 0.011 ab	0.00000452 b	0.00452 b	0.532
L + MR	18.670 ± 2.228 d	0.403 ± 0.021 b	0.086 ± 0.010 c	0.00000337 c	0.00337 c	0.397
L + S	26.330 ± 2.333 bc	0.416 ± 0.007 b	0.121 ± 0.006 ab	0.00000348 c	0.00349 c	0.410
L + SD	21.670 ± 0.720 cd	0.374 ± 0.011 b	0.093 ± 0.003 bc	0.00000338 c	0.00338 c	0.398
L + CC	33.330 ± 1.361 b	0.418 ± 0.019 b	0.148 ± 0.010 a	0.00000365 c	0.00365 c	0.430

The effects of LOM treatments on Cd accumulation in edible parts are listed in Table 4. In the control treatment, BCF and BA were 0.534 and 0.154, respectively. Compared with that in the control, the BCF values in the L + RSC (0.500), L + MR (0.403), L + S (0.416), L + SD (0.374), and L + CC (0.418) treatments were 6.28%, 24.45%, 22.07%, 29.82%, and 21.70% lower, respectively, and the differences were significant ($p < 0.05$), excluding that in the L + RSC treatment. There was a significant difference in BA between L + MR and L + SD, and CK ($p < 0.05$), which decreased by 43.78% and 39.51%, respectively, while the other treatments did not significantly reduce BA. L + MR decreased soil available Cd and transfer from soil to edible parts of *A. selengensis* most efficiently (Table 4).

The $CaCl_2$ extractable Cd decreased in soil treated with different LSF (Table 5). LSF application reduced extractable Cd significantly when compared with that in the control, and the 70%F + L + SD treatment most significantly reduced available Cd content ($p < 0.05$), by 55.89%. Available Cd concentration in soil decreased to a greater extent with 80%F + L + SD and 70%F + L + SD applied than with application of F alone.

Table 5. Effect of LSF on soil available Cd concentration, Cd bioconcentration factor (BCF), and Cd bioavailability (BA) of *A. selengensis*, daily intake of Cd (DIM), Cd-associated health risk index (HRI) and the target hazard quotient (THQ) compared to *A. selengensis* cultivated on Cd-contaminated soil. All values are means of three replicates ± standard errors with different lowercase letters showing significant variability among treatments ($p < 0.05$).

LSF Treatments	Available Cd (μg kg^{-1})	BCF	BA	DIM	HRI	THQ
CK	42.330 ± 1.186 a	0.534 ± 0.036 a	0.154 ± 0.010 a	0.00000568 a	0.00568 a	0.668
F	29.670 ± 1.440 bc	0.432 ± 0.006 b	0.129 ± 0.008 ab	0.00000373 b	0.00373 b	0.439
F + L	23.670 ± 2.126 bcd	0.431 ± 0.023 b	0.110 ± 0.015 bc	0.00000363 b	0.00363 b	0.427
80%F + SD	27.330 ± 2.325 bc	0.442 ± 0.027 b	0.129 ± 0.015 ab	0.00000363 b	0.00363 b	0.427
80%F + L + SD	22.000 ± 2.160 cd	0.433 ± 0.018 b	0.103 ± 0.011 bc	0.00000358 b	0.00358 b	0.421
70%F + SD	30.330 ± 1.785 cd	0.426 ± 0.004 b	0.136 ± 0.008 ab	0.00000368 b	0.00368 b	0.433
70%F + L + SD	18.670 ± 1.963 d	0.419 ± 0.023 b	0.085 ± 0.010 c	0.00000356 b	0.00356 b	0.419

The Cd BCF and BA data for *A. selengensis* in the study area under LSF treatments are listed in Table 5. All the LSF decreased BCF in edible parts significantly ($p < 0.05$) compared with the untreated control, while the difference between treatments was not significant ($p > 0.05$). The BCF value in control was 0.534, and the minimum BCF value was found for the 70%F + L+ SD treatment, at 0.419. BA in the control was 0.534, which was the highest among all treatments. The BA value under the 70%F + L + SD treatment was 0.085, which was a 44.90% reduction when compared with that of CK. Overall, the 70%F + L + SD treatment had the lowest BCF and BA values for Cd.

3.5. Cd Contamination Degree and Human Health Risk

The daily intake of Cd (DIM), health risk index (HRI), and target hazard quotient (THQ) values for Cd are given in Tables 4 and 5. The potential health risks associated with the consumption of Cd-contaminated *A. selengensis* were assessed based on DIM, HRI, and THQ. LOM and LSF treatments had significant ($p < 0.05$) effects on health risks associated with Cd consumption. Among different LOM treatments, the highest DIM and HRI value were observed for the L + RSC and the lowest for the L + MR treatment (Table 4). There were no significant ($p > 0.05$) differences in DIM and HRI of Cd among LSF treatments (Table 5), and the lowest in the 70%F + L + SD. The order of THQ for adults under organic treatments was as follows: L + MR < L + SD < L + S < L + CC < L + RSC. The THQ value order of LSF treatments was 70%F + L + SD < 80%F + L + SD < F + L = 80%F + SD < 70%F + SD < F. The THQ for Cd was < 1, suggesting there was no or negligible health hazard associated with consumption of Cd-contaminated *A. selengensis* under LOM and LSF treatments.

4. Discussion

Agro-ecosystems are being contaminated by Cd due to the long-term application of phosphatic fertilizers, which can cause food safety problems [38,39]. Excessive Cd toxicity negatively affects plant growth, quality, and yield [40]. In the present study, the LOM were a compound organic–inorganic amendment consisting of lime and different organic materials in predetermined proportions. LSF treatments were a compound amendment consisting of different application rates of lime, sawdust, and nitro-compound fertilizer.

Different LOM and LSF treatments improved *A. selengensis* yield (Figures 3 and 4). The improvement in plant growth under different organic–inorganic compound amendment treatments could attribute to the enhancement of nutrient parameters in soil, the reduction of the toxicity of the Cd absorbed (Figures 5 and 6) by *A. selengensis* edible parts, and the decrement in Cd bioavailability in soil (Tables 4 and 5). The maximum decreases in $CaCl_2$-extractable Cd concentrations in soil were observed in the L + MR and 70%F + L + SD treatments across the three seasons. LOM and LSF treatments can improve soil chemical properties and supply nutrients that influence soil quality, further enhancing plant yield, in addition to reducing soil available Cd concentration [41,42]. Lime, as an inorganic amendment, decreases Cd concentration by immobilizing Cd via increased pH in acidic soil [43]. Additionally, organic materials, including rape seed cake, mushroom residue, straw, sawdust, and corn cobs, which contain substantial amounts of organic compounds, can decrease Cd bioavailability in soil and improve soil nutrient status [44–50]. Lime and organic materials applied in combination were a more effective way to optimize soil acidity and improve soil fertility, simultaneously increasing crop yields [51].

The combined effect of organic materials and inorganic compound fertilizers could improve the plant growth environment and crop quality to greater extents than NPK inorganic fertilizer applied alone [52]. According to the results of Hong [53], alkaline phosphorus-containing substances could effectively reduce soil Cd concentration among seven types of P materials, particularly potassium phosphate dibasic (K_2HPO_4). In general, $H_2PO_4^-$ had lower costs and higher solubility in contrast to HPO_4^- [54]. In addition, KH_2PO_4 increased soil pH, which can be attributed primarily to its existence as $H_2PO_4^-$ in soil solution, which exchanges and desorbs OH^- absorbed on soil colloids, thereby decreasing metal solubility [55].

The results of the present study are consistent with previous reports. According to Zhang [56], compared the untreated control, Cd accumulation in the edible part of *A. selengensis* decreased by mixed amendments including NPK compound fertilizer and organic materials. In addition, adding organic amendments could improve plant yield and decrease the bioavailability of Cd in plant tissues. [57]. Furthermore, according to Lahori [58], promoting the immobilization of soil Cd and the reduction uptake by Chinese cabbage shoot Cd following the application of alkaline additives and organic materials. Additionally, Hamid [22] observed the maximum increase in grain yield under a mixed amendment consisting of lime, manure, and sepiolite, due to reduced Cd toxicity with increasing immobilization. A previous study reported that the effects of compound fertilizer on Cd remediation capacity were higher than those under nitrogen or phosphorus fertilizer application alone [59]. In addition, NO_3^- was the preferred nitrogen source for plant uptake due to its greater soil mobility and mass flow driven under plant transpiration [60]. Additionally, according to Hamon [61], KH_2PO_4 has a significant effect on soil Cd fixation through the formation of metal phosphates, which are stable across a broad pH range.

As expected, in the present study, application of LOM and LSF treatments decreased soil available Cd contents in *A. selengensis* plots over three seasons. These observations are attributable to increased soil pH and OM mineralization under the LOM, transforming them from plant-available forms, such as extractable with soluble phosphates, to unusable, such as precipitates [62]. Mohan [63] revealed that Cd^{2+} immobilization capacity increased with an increase in pH because the metal ions in soil solution can form complexes with surface functional groups (-OH and -COOH) in organic amendments. Furthermore, combination of different amendments could prevent Cd from leaching, while reducing Cd availability and toxicity, in contrast with the case in the untreated control [64].

According to He [24], the reduction of exchangeable Cd by organic–inorganic combined amendments primarily through organic matter complexation. Numerous studies have illustrated that because of the presence of surface functional groups such as hydroxyl and carboxyl in organic materials, Cd is immobilized through absorption and precipitation processes [65,66]. Moreover, our results demonstrated that the lower Cd content availability in the soil might also be attributed to the superior soil fertility (Figures 1 and 2, Tables 4 and 5). Zhou [67] revealed differences in Cd availability under different compound amendments associated not only with OM, but also pH and CEC. According to Stewart [68], co-application of organic amendments with lime to contaminated soils could decrease heavy metal bioavailability due to higher pH, OM, and fertility. OM contents are positively associated with soil CEC and influence exchangeable Cd levels [69]. The results illustrate that the minimum soil available Cd content reduction and superior soil fertility were not observed under the same treatment, which can be attributed to the influence of various plant factors, utilization of organic amendments and inorganic compound fertilizers, and soil properties [70].

The results of the present study demonstrated different organic–inorganic compound amendments influenced Cd uptake by edible parts of *A. selengensis* across three seasons (Figures 5 and 6). LOM and LSF treatments diminished Cd concentrations in edible parts of the plant significantly, indicating that the amendments could be used for *A. selengensis* cultivation. Based on the influence of LOM and LSF treatments on Cd accumulation in *A. selengensis*, we discussed the following two conditions. Cd uptake and accumulation in edible parts of a plant be associated with soil-available Cd contents and transformation from soil to the aboveground parts (Tables 4 and 5). Similar results have been reported by Abbas [71], in which Cd was sequestered in roots when amendments were applied, which reduced Cd translocation to aboveground parts. He [25] showed that Cd toxicity in plant tissue was mainly due to the Cd availability in soil, and the *A. selengensis* post-harvest analysis of soil $CaCl_2$-extractable Cd contents revealed that the amendments alleviated soil Cd concentrations significantly (Tables 4 and 5). Accordingly, the main aim of adding organic materials is to alleviate excessive OM decomposition caused by lime and providing OM in soil. The addition of phosphate-induced alleviation of extractable Cd can be ascribed to Cd^{2+} absorption and Cd precipitation [72]. The present study demonstrated that the Cd concentrations in the edible parts of *A. selengensis* in the third season were lower than those in the first season. According to Rehman [37], organic amendments have residual Cd stress alleviation and Cd bioavailability reduction effects in plants. Furthermore, as suggested by Rizwan [73], we assumed that the reductions in Cd concentrations in edible parts under inorganic fertilizer treatments are due to the dilution effects with increasing biomass.

BA and BCF acted as critical measures for evaluating Cd bioavailability and bioconcentration by edible parts of *A. selengensis*, and the potential Cd transformation capacity in contaminated soil. Decreases in BA and BCF values in the present study verified that Cd uptake by plant edible parts was restricted in the soil following application of organic–inorganic compound amendments (LOM and LSF). To assess the health risks associated with consumption of *A. selengensis* cultivated in the Cd-contaminated soil, the DIM, HRI, and THQ were calculated. The DIM value of Cd following consumption of *A. selengensis* grown in soil treatment with amendments was lower than that that in untreated soil. In addition, the HRI value of Cd in *A. selengensis* was <1, indicating safety for consumption by humans. The THQ calculated was less than 1 for local habitants in the survey area, indicating that there was no apparent increase in health risk of Cd intake via *A. selengensis* consumption. In addition, different amendments had various impacts on Cd immobilization in soil, which could be to the specific physicochemical properties of the organic materials, and the diverse nutrient contents of the inorganic compound fertilizers.

5. Conclusions

Application of all organic–inorganic combined amendments (LOM and LSF) mitigated Cd toxicity in the edible *A. selengensis* parts across three seasons. Combined amendments enhanced soil fertility and increased soil pH, while decreasing available Cd significantly. Two experiments were used to assess the Cd bioavailability of LOM and LSF-treated soil in this study. Moreover, the results showed that the L + MR and 70%F + L + SD treatments reduced Cd availability most significantly, because these two treatments had the minimum bioavailability and bioaccumulation, respectively. Under LOM and LSF treatments, consumption of *A. selengensis* demonstrated no health risk. Using the combined amendments above could provide critical soil nutrients, improve Cd immobilization, and minimize health risks. However, further research should be conducted to evaluate the remediation effects of the current amendments on different plants, in addition to the Cd speciation characteristics and Cd uptake mechanisms by the plants.

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