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Original Research

Fractions and Bioavailability of Cadmium and Nickel to Carrot Crops in Oasis Soi

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Abstract

The Hexi Corridor is the most important area for desert oasis farming in northwestern China. Due to persistent drought and water shortage, sewage irrigation is widely used in this area. Heavy metal pollutants contained in the sewage could remain in the surface layer of agricultural soil and accumulate in plants. Our research used pot experiments to evaluate carrot crop (*Daucus carota* L.) production, heavy metal uptake, and bioavailability under single cadmium (Cd) or nickel (Ni) contamination and compound (Cd-Ni) contaminations in irrigated desert oasis soil. The results show that Cd existed in the Fe-Mn oxide bound fraction and Ni presented in the residual fraction mainly in original (control) soils. Low concentrations of Cd could promote the growth of carrots, while high concentrations of Cd significantly restrain the growth of the crops. However, Ni had a poisonous effect on the carrots even at the lowest concentrations. There was an antagonistic effect between Cd and Ni in the compound contaminated oasis soils. The bio-concentration factors (BCF) of Cd in carrots were higher than those of Ni, and the BCF of Cd and Ni in single-contaminated soils were higher than those in compound-contaminated soils. Cd and Ni contents in different parts of the carrots were correlated with the exchangeable fraction in contaminated oasis soils, which would cause potential risk to human health through the food chain.

Keywords: fraction, bioavailability, cadmium, nickel, carrot crops, oasis soil

Introduction

Extensive mineral resources are characterized by large quantities of ores containing cadmium, copper, nickel, lead, zinc, and iron in the arid land of northwestern China. Due to drought and water shortage, long-term industrial waste water and urban sewage irrigation is used, which results in the remains of heavy metals in agricultural soil. Heavy metals such as Cd, Ni, Pb, and Cu in soils cannot bio-degrade, but can be bio-accumulated by plants [1, 2]. Excessive heavy metals accumulation in plants would expose people to a high health risk [3-5].

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Determining the total content of heavy metals and their chemical fraction may provide useful information about metal bioavailability and toxicity to the plant, so fraction analysis is usually employed to characterize the behavior of heavy metals in soil [6-10]. There are many methods to classify and determine the chemical fractions of heavy metals. The Tessier scheme is still the most effective method to devise fractions from total metals [11-13]. The classifications are: exchangeable fraction (EXC-F), carbonate bound fraction (CAB-F), Fe-Mn oxide-bound fraction (FMO-F), organic-bound fraction (OM-F), and residual fraction (RES-F) [13].

Oasis agriculture plays an important role in the development of inland areas. Carrot crops (*Daucus carota* L.) are

Table 1. The main characteristics and the initial contents of heavy metals in the experimental soils.

Soil type	Soil	CEC	OM	$CaCO_3$	Cd*	Ni
	pH	(meq/100g)	(%)	(%)	(mg/kg, DW)	(mg/kg, DW)
Irrigated silt sandy soil	8.1	9.8	1.23	12	0.16	41.36

*background concentration levels of Cd, Ni in oasis region.

Table 2. Treatments with different concentrations of Cd and Ni (units: mg/kg) (n=81).

Treatments	CK*	1	2	3	4	5	6	7	8
Cd	0	0.35	0.75	1.25	1.80	2.50	3.50	5.00	7.50
Ni	0	60	110	170	250	350	500	750	1100
Cd-Ni	0	0.35+60	0.75+110	1.25+170	1.80+250	2.50+350	3.50+500	5.00+750	7.50+1100

*CK – control

richly nutritious and are a popular, healthy food that is planted and eaten widely throughout the world. Cd and Ni contamination are the dominant pollutant elements in oasis-irrigated soil [3, 4]. However, the bioavailability of Cd and Ni to carrots in the irrigated oasis soil in Northwest China has not been reported. In addition, there are few reports about Cd-Ni transference and conversion from soil to the crops system.

This paper analyzes the total contents and the fraction of Cd and Ni in oasis soil by employing the Tessier scheme, and evaluates the bioavailability of Cd and Ni to carrot crops using Pearson coefficients.

Materials and Methods

Physical Description and Soil Sampling

The size of the oasis region in northwestern China is about 104,000 km^2. The oasis region is subject to a continental semi-arid climate (altitude = 1380-2278 m, annual precipitation =118.4 mm, annual mean air temperature = 7. 7ºC). Pot experiments were conducted under open air conditions in 2008 at Linze County (39º04′~39º24′N, 99º35′~100º25′E), Hexi corridor, Northwestern China. The elevation ranges from 1,500 to 1,800 m. This area belongs to a semi-arid region with low precipitation (104~129 mm annually), high evapotranspiration (1900~2100 mm), and high temperatures in the summer (22ºC). The experimental soil type belongs to an irrigated silt sandy soil and the textures were mainly sandy.

The experimental soils excavated from an oasis farm were passed through a 2 mm fiber-sieve, air dried, and mixed in a heap for analysis. The pH of soil (1:5 soil-water ratios) was measured by a glass electrode, organic matter (OM) content was determined using the Tyurin method [14], cation exchange capacity (CEC) was measured by the ammonium acetate method [14], and calcium carbonate content ($CaCO_3$) was determined using the carbon dioxide volume method. The main characteristics and the initial contents of heavy metals in the experimental soils are shown in Table 1.

Pot Experiments

Prepared soil samples (0-15 cm) weighing 6 kg (dry weight) and placed in each plastic pot for growing the carrot plants. According to the field pollution investigation from the Bainyin oasis region where soil type is an irrigated silt sandy soil, the concentration of Cd and Ni ranged from 0.161-7.75 mg/kg and 41.36-1178.17 mg/kg, respectively [2]. In order to imitate the uptake of Cd and Ni by carrots under multi-metal contamination in irrigated silt sandy soil, we used the experiment and designed nine treatments (one control and eight treatments) from minimum to maximum concentration values of each heavy metal based on the field pollution investigation [1, 2]. Eight treatments were used to distribute the concentration evenly and each treatment was replicated three times [15].

The control soil had initial contents of heavy metals. The spiked soil samples were amended once with a solution of different concentrations of $Cd(NO_3)_2$ and $Ni(NO_3)_2$, in order to increase the concentration of heavy metals in the soils (Table 2). The spiked soils were mixed by hand and turned thoroughly several times. Before planting the seeds, soil samples were left to equilibrate in plastic boxes covered with plastic film for two months. Soil moisture content remained at 70% of the water-holding capacity after the treatment. The pot is 20 cm tall and the diameter of the pot is 15 cm. The pots were arranged randomly inside a netted greenhouse. Seeds were sown directly to the soil pots in late March, which is the normal growing season for carrots in Linze County and also arid areas in northwestern China. During the experimental period, each pot kept four plants, tap water was added to compensate for evaporation and transpiration, and soil moisture content was maintained at approximately 70% of the water-holding capacity. In late June, the carrot samples were harvested. The number of soil samples, 81, includes (9×3) treatments×3 replicates.

Table 3. Fractions content of Cd under different Cd treatments of soil cultivated with carrots (units: mg/kg) (n=27).

Treatments	CK	1	2	3	4	5	6	7	8
Cd-EXC	0	0.02	0.02	0.12	0.16	0.26	1.05	1.40	1.96
Cd-CAB	0.03	0.20	0.24	0.34	0.60	0.98	2.20	2.76	3.80
Cd-FMO	0.06	0.18	0.22	0.28	0.32	0.36	0.74	1.34	1.32
Cd-OM	0	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.03
Cd-RES	0.01	0.02	0.02	0.03	0.02	0.03	0.03	0.04	0.07

Values were the mean of three replication samples.

Table 4. Fraction contents of Ni under different Ni treatments of soil cultivated with carrots (units: mg/kg) (n=27).

Treatments	CK	1	2	3	4	5	6	7	8
Ni-EXC	0.12	0.17	0.81	1.24	1.81	2.60	2.45	2.87	3.58
Ni-CAB	0.28	4.11	14.49	17.34	24.46	33.94	49.47	57.78	95.65
Ni-FMO	5.40	26.23	86.62	116.28	153.25	240.33	389.67	567.42	723.65
Ni-OM	9.86	14.16	32.32	41.38	53.61	75.42	115.44	171.46	192.54
Ni-RES	24.41	24.51	25.62	28.43	26.72	29.23	36.23	38. 40	42.32

Values were the mean of three replication samples.

The carrot crops were separated into two parts: leaves and roots. After removing the soil particles with tap water, the leaves and roots were washed with de-ionized water three times respectively. Then the samples were dried in an oven at 70ºC for 48 hours and stored for further analyses. The number of plant samples was 162, including (9×3) treatments×(3 $replicates_{leaf}$ +3 $replicates_{root}$) used for accumulation of heavy metals in carrot. The number of plant samples was 54, including 9 compound treatments× (3 $replicates_{leaf}$ +3 $replicates_{root}$) for carrying out the correlation analysis.

Determination of Total Content of Cd and Ni in Soils and Carrots

The total contents of Cd and Ni in each soil treatment were extracted by HNO_3+HF+$HClO_4$ solution, and the heavy metals in the plants were extracted using HNO_3+$HClO_4$ digestion. All digested samples were diluted to 50 ml with 0.5% HNO_3 and stored at 4ºC until the concentrations of selected heavy metals were analyzed. Total metal contents were determined by an atomic absorption spectrometer (AAS) and a graphite furnace (M6MKII, Thermo Fisher, USA).

Fraction Analysis of Cd and Ni in Soils

Fraction analysis of heavy metals in spiked soils was carried out on 1.0 g aliquots of soil according to the Tessier scheme. The five-sequential extraction procedure includes extracting the EXC fractions by 8 ml of 1 M $MgCl_2$ (pH 7.0) in a 50 ml centrifuge tube with shaking for 1h at room temperature; the CAB fractions by 8 ml of 1 M NaOAc (pH 5.0) with shaking for 5 h at room temperature; the FMO fractions by 20 ml of 0.1 M NH_2OH·HCL in 25% (v/v) HOAc with shaking for 6h at 96±3ºC; the OM fractions by 3 ml of 0.02 M HNO_3 and 5 ml 30% H_2O_2 (pH 2.0) with shaking for 3 h at 85±2ºC, and then adding 15 ml of 1 M NH_4OAc in 20% (v/v) HNO_3 with shaking for 30 min at room temperature; and the RES fractions by HNO_3-HF-$HCLO_4$.

Quality Control

All experimental glassware and containers were soaked in 20% HNO_3 for at least 12 h previously and rinsed with de-ionized water before use. In order to ensure the precision of the experimental process, three duplicates and one standard reference sample, GSS-2 (GBW-07401) and GSV-2 (GBW-07403), were used for analysis. The correlation and regression analysis between the metal fraction in soils and the bioavailability assessment of heavy metals in carrots was carried out with SPSS 13. Standard recovery and precision were found to be within 100±5%.

Results and Discussion

The Fraction Distributions of Cd and Ni in Soils

The fraction contents of Cd and Ni in soils under single Cd or Ni contamination are shown in Tables 3 and 4, respectively. The fraction contents of Cd and Ni in soils under compound (Cd-Ni) contamination are shown in Table 5. The parameter fraction distribution coefficient

Table 5. Fraction contents of Cd and Ni under compound treatments in soil cultivated with carrots (units: mg/kg) (n=27).

Treatments	CK	1	2	3	4	5	6	7	8
Cd-EXC	-	0.01	0.03	0.06	0.11	0.23	0.74	1.17	1.66
Cd-CAB	0.03	0.13	0.37	0.78	0.97	1.39	2.57	3.07	3.75
Cd-FMO	0.06	0.06	0.13	0.18	0.21	0.42	0.64	0.82	1.03
Cd-OM	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Cd-RES	0.01	0.02	0.05	0.04	0.02	0.02	0.03	0.04	0.02
Ni-EXC	0.12	0.65	1.30	1.74	2.43	3.78	5.07	6.34	6.69
Ni-CAB	0.79	11.15	19.64	24.47	33.92	50.77	65.94	86.95	106.45
Ni-FMO	5.40	26.07	43.02	59.89	85.87	131.85	207.80	271.45	383.91
Ni-OM	9.85	14.91	18.57	23.19	24.82	38.81	57.08	68.61	95.34
Ni-RES	23.43	25.06	24.70	25.24	25.47	25.94	33.43	29.94	34.32

Values were the mean of three replication samples.

(FDC) was defined as the one metal fraction content accounting for the percentage by total amount of the same metal [3]. The FDC of Cd in soils under single Cd and compound contamination are shown in Figs. 1 (a) and (b), and the FDC of Ni in soils under single Ni and compound contamination are shown in Figs. 2 (a) and (b), respectively.

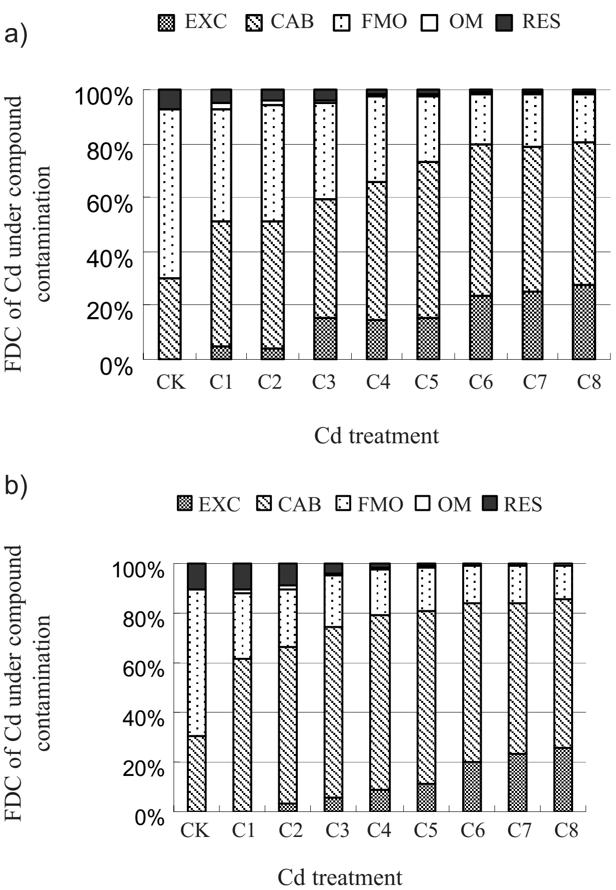

Fig. 1. Change of the FDC of Cd in soils with different treatments: (a) under single Cd contamination, (b) under compound contamination.

The results showed that Cd was mainly present in FMO-F and Ni in RES-F, in original (control) oasis soils. Under single Cd contamination, the EXC-F, CAB-F, and FMO-F increased significantly with increasing Cd concentration (Table 3), but the contents of Cd in OM and RES changed very little. Under compound contamination, the fraction contents of Cd showed similar characteristics to those under single Cd contamination (Table 5). Under single Cd contamination, the FDC results showed that the EXC-F and CAB-F increased significantly with the increase of Cd concentration. However, the FMO, OM, and RES fraction of Cd decreased gradually. In addition, the primary fraction of Cd was CAB-F in all treatment soils due to the high pH value in irrigated desert soils (pH = 8.16). When the pH value of soil is higher than 7, Cd mainly exists in CAB. Compared with the FDC results under single Cd contamination, the development of the FDC of Cd under compound contamination exhibited the same trend. Similar results found that the percentage of heavy metals associated with EXC fraction and CAB fraction increased with the increasing total amount of heavy metals [16, 17].

When Ni was employed as a single contamination (Table 4), the contents of Ni in all five fractions increased with increasing Ni concentrations. The FDC of Ni in EXC-F initially increased and then decreased from the No. 6 treatment, the CAB-F and FMO-F increased significantly, OM-F changed little, and RES-F decreased dramatically. The fractions' contents and the FDC of Ni under compound contamination showed a similar tendency to those under single Ni contamination. The FDC values of Ni in OM-F were high and ranged from 14.76% to 20.57% under both single and compound contamination. This is consistent with a previous study [18] that reported that the Ni element is easily immobilized by organo-mineral phases in alkaline soils. In the present study, Ni content in EXC-F in soils was lower than 1.5%, suggesting that the available fraction of Ni was very low.

Table 6. Fresh weight of leaves and roots of carrot under different treatments (units: g/pot) (n=162).

Treatment No.	Fresh weight under Cd contamination		Fresh weight under Ni contamination		Fresh weight under (Cd+Ni) contamination	
	Leaves	Roots	Leaves	Roots	Leaves	Roots
CK	9.19±1.99[bc]*	12.30±4.25[b]	9.20±1.99[d]	12.30±3.25[d]	9.19±2.13[b]	12.30±0.37[d]
1	9.49±1.03[bc]	12.51±2.11[ab]	7.70±1.80[cd]	8.05±2.17[c]	6.40±2.47[bc]	7.13±1.83[c]
2	10.31±1.55[ab]	13.82±6.32[b]	5.57±2.21[bc]	5.07±1.94[bc]	6.55±3.12[bc]	6.48±1.65[c]
3	10.39±2.34[bc]	13.75±2.82[b]	3.94±2.13[b]	3.25±1.84[ab]	5.26±1.32[b]	4.45±0.94[bc]
4	12.13±1.08[bc]	14.45±1.53[ab]	0.74±0.41[a]	0.13±0.11[a]	6.55±2.47[bc]	5.77±0.76[c]
5	11.89±3.14[ab]	14.31±3.12[ab]	0.23±0.17[a]	0.07±0.78[a]	3.73± 0.87[b]	1.70±0.34[ab]
6	12.40±0.97[bc]	14.89±1.86[b]	-	-	0.37±0.12[a]	0.14±0.08[a]
7	8.32±1.23[c]	9.27±3.49[b]	-	-	0.17±0.08[a]	0.04±0.02[a]
8	5.20±0.91[a]	5.12±1.55[a]	-	-	0.14±0.07[a]	0.03±0.02[a]

"-" – No plant

*In each column with same letter means it has no significantly different at the 0.05 level according to LSD test.

The results also show that the bioavailability fraction of Cd was much higher than that of Ni, which demonstrates that the activity of Cd was stronger than Ni, and its toxicity was correspondingly greater than Ni. Compared with the FDC of Cd/Ni under single Cd or Ni contamination, no remarkable changes could be observed from those under compound contamination. This indicates that the addition of Ni/Cd had a weak effect on the fraction of Cd/Ni in soils.

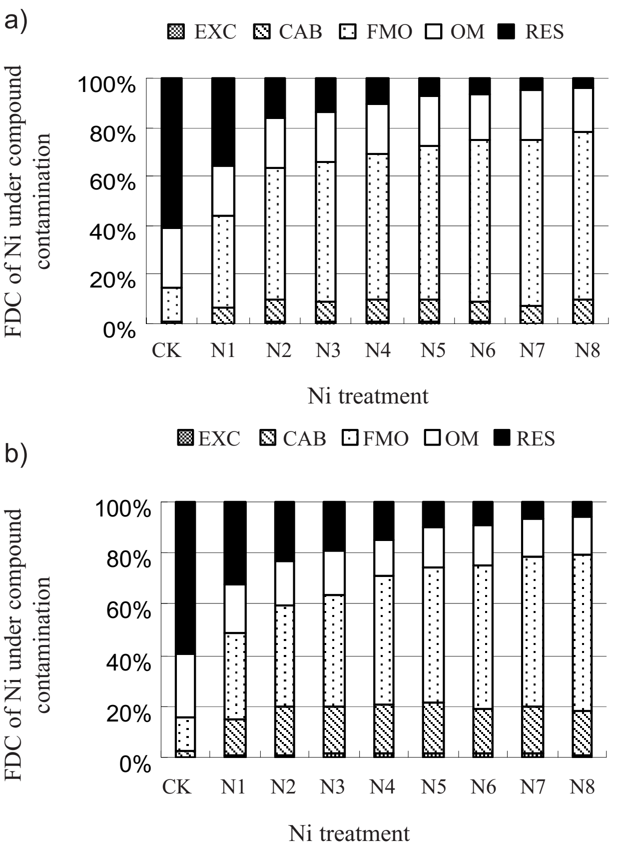

Fig. 2. Changes of the FDCs of Ni in soils with different treatments: (a) under single Ni contamination, (b) under compound contamination.

Growth Status of Carrot in the Soils

The fresh weight of leaves and roots of carrots grown in different types of contamination soils is shown in Table 6. The table shows that the fresh weight of roots and leaves of carrots under single Cd contamination increased and reached peak value when the concentration of Cd was 3.50 mg/kg (Treatment 6). Once the concentration is higher than in Treatment 6, the roots of carrots can be damaged and might be restrained from absorbing nutritional elements. These results indicate that appropriate concentrations of Cd could promote the growth of carrots, but excessive Cd could restrain this condition. This conclusion is similar to the results of previous studies [19]. When increasing the treatments of Ni, the fresh weight of leaves and roots of carrots grown in soils under single Ni contamination decreased. It was especially evident that the fresh weight of leaves and roots decreased sharply when the concentration of Ni increased at 250 mg/kg (Treatment 4). The results indicate that Ni is poisonous to carrots.

Under compound contamination, the fresh weight of leaves and roots of carrots decreased as the treatments were increased, which is a similar result to that under single Ni contamination. However, the fresh weight of leaves and roots of carrots grown under compound contamination was higher than that under single Ni contamination, attributing to the positive effect of the Cd element.

The Bioavailability of Cd and Ni in the Carrot Plant

Accumulation of Cd and Ni in the Carrot Plant

Total contents of Cd and Ni in carrots increased with increasing Cd and Ni treatments (Tables 7 and 8). Nearly half of Cd and most Ni accumulated in the edible part (roots) of the carrots, which would bring a potential risk to human health through food chains. However, contents of

Table 7. Heavy metals content in carrots cultivated in single-contaminated soils (units: mg/kg) (n=108).

Treatment No.	Cd content under Cd contamination		Ni content under Ni contamination	
	Leaves	Roots	Leaves	Roots
CK	0.08±0.30[a]*	0.06±0.01[a]	0.75±0.18[a]	2.53±1.54[a]
1	0.32±0.03[a]	0.27±0.05[ab]	8.52±0.87[b]	11.20±3.60[ab]
2	0.38±0.13[a]	0.39±0.07[ab]	21.37±1.20[b]	27.53±6.67[bc]
3	0.55±0.23[b]	0.65±0.03[b]	27.59±0.19[c]	38.72±8.56[bc]
4	0.86±0.15[bc]	1.02±0.01[bc]	35.45±3.20[d]	54.52±7.69[e]
5	2.80±0.22[c]	1.85±0.22[c]	37.33±3.65[d]	101.47±16.88[e]
6	7.45±0.37[d]	4.56±0.28[e]	-	-
7	8.95±0.46[e]	6.95±0.42[ef]	-	-
8	12.27±0.60[e]	9.18±0.33[f]	-	-

"-" – No plant.
*Each column with the same letter means it is not significantly different at the 0.05 level according to the LSD test.

Table 8. Heavy metals content in carrots cultivated in compound-contaminated soils (units: mg/kg) (n=54).

Treatment No.	Cd content under Cd contamination		Ni content under Ni contamination	
	Leaves	Roots	Leaves	Roots
CK	0.07±0.01[a]*	0.06±0.01[a]	0.74±0.08[a]	2.52±0.79[a]
1	0.34±0.03[a]	0.26±0.05[ab]	4.89±0.30[a]	5.92±1.07[a]
2	1.26±0.13[ab]	0.29±0.07[ab]	6.83±0.14[ab]	7.06±2.11[ab]
3	1.72±0.05[bc]	0.45±0.03[b]	9.43±0.45[ab]	11.08±2.78[ab]
4	2.45±0.05[cd]	0.66±0.01[bc]	15.02±0.89[c]	20.08±2.91[bc]
5	4.55±0.42[d]	1.52±0.22[c]	20.33±1.30[d]	39.93±3.60[d]
6	4.55±0.47[e]	3.29±0.42[ef]	26.05±1.78[e]	69.52±12.60[d]
7	5.17±0.71[e]	4.45±0.33[f]	43.72±2.56[f]	164.11±20.88[e]
8	5.89±1.36[f]	5.42±1.03[f]	55.58±3.74[f]	288.54±35.74[f]

*Each column with the same letter means it is not significantly different at the 0.05 level according to the LSD test.

Cd (except Cd contents in leaves in Treatments 2~5) and Ni in carrots under compound contamination were lower than those under single Cd or Ni contamination, which indicates that there is an antagonistic effect between Cd and Ni in the compound-contaminated oasis soils. However, by employing Treatments 2~5, contents of Cd in leaves under compound contamination were higher than those in single Cd contaminated soils, which indicates that Cd-Ni compound had a synergistic effect on Cd in the leaves of carrots in oasis soils. Ni at a suitable concentration (ranging from 110 mg/kg to 350 mg/kg) could promote Cd uptake in carrots. A previous study reported that Cd-Zn pollution had an antagonistic effect on Cd, and high content of Zn could restrain Cd uptake in vegetables grown in purple soil [20]. However, Cd-Zn compound contamination had a synergistic effect on Zn, and a low content of Cd could promote Zn uptake in wheat, lettuce, tomato and cabbage in purple soil. But there are few studies about the interaction of Cd and Ni under Cd-Ni compound contamination.

The bio-concentration factor (BCF) and the translocation factor (TF) were employed to investigate and compare the bioavailability of Cd and Ni to carrots in the soil-carrot system. In this study, BCF is the ratio of the metal concentration in carrot roots to that in the rooted soils, and TF is the ratio between the metal concentration in the leaves and that in the carrot roots. The BCF of Cd and Ni under single and compound contamination in different treatments are shown in Fig. 3. When increasing the single Cd treatments, the BCF of Cd1 in carrot increased. The BCF of Cd2 under compound contamination also increased when increasing the treatments. The similar tendencies of Ni could also be observed from the BCF curve of Ni1 and Ni2. However, the BCF values of Cd were more than for Ni, indicating that the removal rate of heavy metals from soils to carrot is Cd>Ni.

Table 9. Correlation coefficient (*R*) between the FDC of Cd and Ni, and their contents in carrots under compound contamination (n=54).

Fractions	*R* (Cd)		*R* (Ni)	
	Leaves	Roots	Leaves	Roots
EXC	0.891**	0.885**	0.727*	0.773*
CAB	0.892*	0.775*	0.752	0.820
FMO	0.578	0.539	0.372	0.753*
OM	-0.755*	-0.654	0.59	0.712
RES	-0.576	0.472	-0.445	-0.749*

*Significance at level p<0.05; **significance at level p<0.01.

Many studies indicate that most vegetables can accumulate Cd at a high rate [21-22]. In addition, the BCF values of both Cd1 and Ni1 under single contamination were higher than those under compound contamination (except the BCF of Cd with Treatment 2), which indicated that there was an antagonistic effect between Cd and Ni upon their uptake.

The TF of Cd and Ni under single and compound contamination with different treatments is shown in Fig. 4. It was found that the TF values of Cd in single and compound contamination were higher than 1, while the TF values of Ni were lower than 1. This indicates that the translocation capacity of Cd from roots to leaves in carrots is stronger than that of Ni. Cd was mainly accumulated in the leaves of the carrots, but more Ni accumulated in the roots of the carrots. Additionally, the TF of Cd2 increased and reached peak value at Treatment 2, and then decreased under compound contamination with increasing treatments, while the TF of Ni2 showed little change. The results indicate that Ni at a low concentration could promote the translocation capacity of Cd from roots to leaves in carrots.

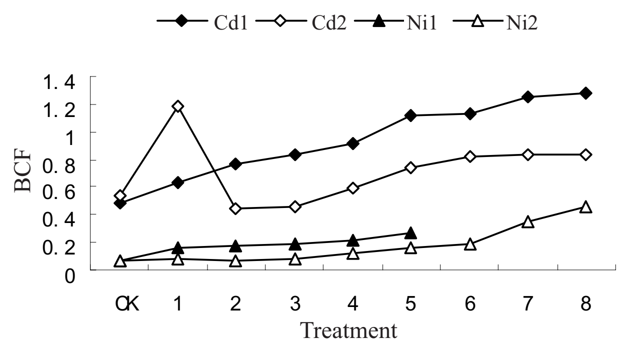

Fig. 3. Changes of BCF of Cd and Ni with different treatments: Cd1 under single-Cd contamination, Ni1 under single-Ni contamination, Cd2 under Cd-Ni contamination, Ni2 under Cd-Ni contamination.

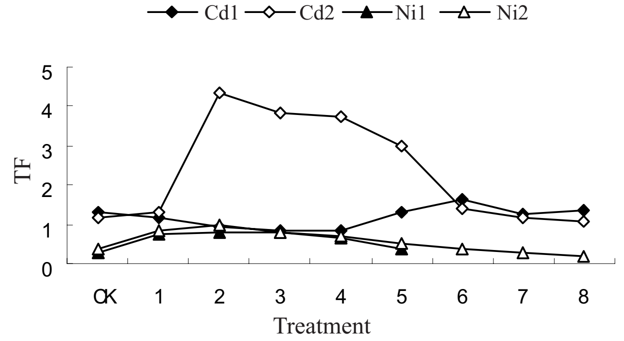

Fig. 4. Changes of TF of Cd and Ni with different treatments: Cd1 under single-Cd contamination, Ni1 under single-Ni contamination, Cd2 under Cd-Ni contamination, Ni2: under Cd-Ni contamination.

Relationship between the Uptake of Cd and Ni in Carrots and Their Fractions in Soil

A significant (p<0.05) positive relationship between Cd content in carrot and the FDC of Cd in EXC in soils is found in Table 9. The corresponding correlation coefficients (R) were 0.891 for leaves and 0.885 for roots. A similarly significant positive correlation was found between Ni content in the roots of carrot and the FDC of Ni in EXC in soils. The corresponding correlation coefficients were 0.773 for roots. The results suggest that Cd and Ni in EXC-F were easily taken up by the carrots. Zhu found that the exchangeable fraction of Cd was most available and contributed the most to the lettuce plant in purple soil [20]. Guerra also found that exchangeable fraction of Ni has a high availability in the soil-ryegrass system and could be taken up by ryegrass shoots [23]. In the present study, both the exchangeable fractions of Cd and Ni were available to the carrots.

Conclusions

The results show that Cd existed in the FMO fraction and Ni was presented in RES in original (control) soils. With the increasing contents of the two metals in the oasis soil, the fractions' distribution of Cd and Ni changed significantly. Low concentrations of Cd could promote growth of the carrots while high concentrations of Cd significantly restrained the growth of the plants. However, Ni had a poisonous effect on the carrots even during No. 1 treatment. There was an antagonistic effect between Cd and Ni in the compound-contaminated oasis soils. The bio-concentration factors (BCF) of Cd in carrot were higher than those of Ni, and the BCF of Cd and Ni in single-contaminated soils were higher than those in compound-contaminated soils. The translocation factors (TF) of Cd was slightly higher than 1, while the TF of Ni was lower than 1. This indicates that Ni at a suitable concentration (ranging from 110 mg/kg to 350 mg/kg) could promote the translocation capacity of Cd from roots to leaves in the carrot plant. Cd and Ni contents in different parts of the carrot were mainly correlated with the EXC-F in contaminated oasis soils, which can cause a potential risk to human health through the food chain.

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