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CHELATING RESIN MEMBRANE METHOD FOR ESTIMATION OF SOIL CADMIUM PHYTOAVAILABILITY

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ABSTRACT: A metal chelating exchange resin membrane was used to extract soil cadmium (Cd) and to evaluate the plant uptake of Cd from soils. Eight soils with widely varying properties and Cd levels were tested. Soil suspensions (4 g in 40 mL deionized water) were equilibrated with 5 cm² Ca-Chelex membrane which was retained inside a polypropylene bag and shaken at 150 rpm for 24 hrs. Resin membrane extractable Cd of the soils were correlated with Cd uptake by young wheat seedlings grown in these soils and compared with soil Cd extracted by several commonly used chemical extractants. The amounts of Cd extracted by the Ca-Chelex membrane from all tested soils were correlated with those absorbed by young wheat seedlings or those extracted by the tested chemical extractants. The Ca-Chelex membrane extractable Cd of the soil, however, had the strongest correlation with plant uptake Cd. It was demonstrated that the Ca-Chelex membrane extraction is an appropriate method in estimating Cd phytoavailability of soil and is applicable to a wide range of soils.

INTRODUCTION

Cadmium is by far the most concerned environmental pollutant of soil. It is readily absorbed by plants and may enter the human food chain (Chang et al., 1983) thus presenting a potential health risk to consumers. Therefore, it is essential that the Cd phytoavailability of soils can be accurately estimated. Several soil diagnostic tests have been developed to estimate Cd phytoavailability (Baker

and Amacher, 1982; Risser and Baker, 1990). They usually involve equilibrating the soils with (i) dilute extractants such as water and neutral electrolyte solution (e.g. 0.01M CaCl₂), (ii) strong extractants such as mineral acids (e.g. 0.1M HCl), or (iii) metal chelating extractants such as 0.005M Diethylenetriaminepentaacetic acid (DTPA) and is followed by determination of soil Cd extracted by these extractants. However, Cd found in dilute extractants only represents concentration of Cd in equilibrium with Cd in solid phase. But it does not account for the ability of a soil to buffer or replenish Cd in the solution phase. Conversely, strong acid extractants may change the soil to conditions greatly different from those where plants are grown and cause soil minerals to dissolve. Amounts of Cd extracted under such circumstances may have little relationship to the portion of soil Cd that is available to plants. Chelating reagents are thought to extract a fixed portion of the soil's Cd-chelating sink (Risser and Baker, 1990). These methods have been successful in estimating soil Cd phytoavailability under limited conditions. But none of the methods is able to predict consistently the phytoavailability of Cd for soils of various physical and chemical properties. For example, the acid extractants generally are not suitable for calcareous soils unless the soil pH and other soil characteristics are considered. When DTPA is used to extract metal in acid soils, soil pH should be included in for interpreting the results (Baker and Amacher, 1992)

Another approach to estimating Cd phytoavailability of soil is to introduce a strong or infinite sink for soil Cd to react with. At the end, the sink is recovered and the amount of Cd removed by the sink is determined. The infinite sink method is chemically less destructive to the soil and its reaction with the soil resembles the way plants extract elements from the soil. The anion-exchange resin and iron oxide-impregnated filter paper have been used as infinite sinks in extracting available P from soils (Amer et al., 1955; Lin et al., 1991). A chelating resin, which concentrates heavy metal in aqueous solutions (Figura and McDuffie, 1977, 1979, 1980), may provide such a sink for estimating phytoavailability of soil Cd. It can selectively adsorb heavy metal cations (such as Cd) at the presence of common metal cations (such as Ca, Mg, and K) in the soil solution. Amounts of Cd the resin is able to react with are controlled by the chemical potential of the soil metal. Jing and Logan (1991, 1992) used a chelating resin to estimate sludge Cd

phytoavailability. In their method, Chelex 100 resin beads (Bio-Rad Laboratories, Dow Chemical) were used. Because the commercially available resins are small in particle size (50-100 mesh), it is difficult to retrieve once added into the sludge. A dialysis tube was used to retain the resin. We used a chelating exchange resin membrane to test Cd phytoavailability of a wide range of soils which were different in physical and chemical properties and contained varying amounts of Cd. The results were compared with those obtained by chemical extraction methods and Cd absorption by wheat seedlings grown on these soils.

MATERIALS AND METHODS

Preparation of Resin Membrane: Sheets of Na-form chelating resin membrane (Chelex 12" x12" membrane sheets, Bio-Rex ion exchange membrane sheets, Bio-Rad) were cut into 1 cm x 5 cm pieces. The small pieces of membranes were first immersed in deionized water for 2 days and then placed in a glass column and eluted by 2M CaCl_2 solution at the flow rate of 2.5 mL/min until the Ca concentration in the outlet solution equaled to that in the inlet solution. After the Na-form membranes were transformed to Ca-form membranes, they were thoroughly rinsed and stored in deionized water for use.

The spent membranes were regenerated by first eluted with 1M HCl solution at the flow rate of 2.5 mL/min in a glass column until the Cd and Ca in the outlet solutions can no longer be detected. The residual acid on the membrane was washed out by deionized water. To transform the membrane into the Na-form, 1M NaOH solutions were passed through the column. The Na-form resin membranes were further treated with 2M CaCl_2 to transform them into Ca-form membranes.

For separating membranes from soil particles, bags made from polypropylene (PP) netting (60 mesh) were used to retain the resin membrane during the course of extraction. The bags were immersed in 1M HCl overnight and then rinsed with distilled water and oven-dried before use.

Kinetics of Cd Adsorption by Chelating Resin Membrane: A series of 50-mL centrifuge tubes each with one piece of the resin membrane (5 cm²) in a bag were filled with 40 mL of 0.005M $\text{Ca}(\text{OAc})_2$ solution containing 5.7 mg/L Cd. The tubes were then shaken at 150 rpm and 25°C for periods ranging from 2 to 36 hrs. At the end of shaking periods, the resin membranes along with the bags

were recovered, rinsed thoroughly with deionized water, and air-dried. The pH of the solutions was measured after the removal of resin membrane bags. The membranes were then placed into a set of 50-mL centrifuge tubes containing 40 mL aliquots of 1M HCl and the tubes shaken for 24 hrs to desorb the Cd adsorbed on the membrane. The desorption process was repeated once. Cadmium in the solutions was determined by atomic absorption spectroscopy.

Cadmium Adsorption Isotherms of Chelating Resin Membrane: In this experiment, a series of 50-mL centrifuge tubes were filled with 40 mL of 0.005M $\text{Ca}(\text{OAc})_2$ containing various amounts of CdCl_2 and adjusted to several pH levels. Each tube also contained one piece of Ca saturated resin membrane (5 cm^2) in a PP bag. The tubes were then shaken at 150 rpm and 25°C for 24 hrs. At the end of equilibration, the resin membranes along with the bags were recovered, rinsed thoroughly with deionized water, and air-dried. The pH of the solutions was measured after the removal of resin membrane bags. Cadmium adsorbed by the membranes was desorbed in two 40-mL aliquots of 1M HCl and measured by atomic absorption spectroscopy.

Extracting Soil Cd by Resin Membrane: Four-gram of soil (passed through 80 mesh), 40 mL of deionized water, and one piece of Ca-Chelex resin membrane (5 cm^2) in a PP bag were placed in a 50-mL centrifuge tube. The tubes were shaken for 24 hrs. The soil suspensions were decanted and the resin membrane was recovered, rinsed thoroughly with distilled water, and air-dried. It was then transferred into a clean 50-mL centrifuge tube and 40-mL aliquots of 1M HCl added. The tube was shaken for 24 hrs to desorb the Cd from the membrane. The Cd desorption procedures were repeated once. The Cd concentrations in the aliquots of 1M HCl were determined by atomic absorption spectroscopy.

Cadmium Uptake by Young Seedlings of Wheat: A modified Neubauer method (Lee, 1983) was used to determine plant-extractable soil Cd. A series of plastic bottles (10 cm diameter x 7.5 cm high) were filled with the mixture of 90 g of the soil and 50 g acid-washed quartz sand (10-30 mesh). Three-mL of solutions containing 2.4% $(\text{NH}_4)_2\text{SO}_4$, 0.9% KNO_3 , 3.3% MgSO_4 , and 1.2% KH_2PO_4 were added to the mixture in each bottle. Sufficient amounts of distilled water were then added, by weighing, to bring each soil to field capacity. The bottles were left standing for 2 days for the solution and solid mixture to come to equilibrium. Afterward, 100 mg acid-washed quartz sand were added to each

bottle and spread evenly over the surface with a spatula. A template was used to mark the surface with 88 evenly spaced holes, and one wheat seed (variety Taichung select No. 2) was placed in each hole. Another 50 g of quartz sand were added to cover the seeds, and distilled water was added as required. Each experimental treatment was triplicated. The experiment was carried out in a phytotron at $25 \pm 5^\circ\text{C}$ for 35 days.

At the end of the experiment, seedlings including roots were washed free of quartz sand and soil, oven dried at $70\text{--}80^\circ\text{C}$ for 48 hrs, ground to pass a 60-mesh sieve, and stored for analysis. Two hundred mg of plant tissue sample were placed in a digestion flask with 5 mL conc. H_2SO_4 and heated on a hot plate until it turned into a dark colored solution. Then, 1 mL of mixed $\text{H}_2\text{SO}_4\text{:HClO}_4$ acids (92:8 by volume) was added and the digestion continued further to a colorless solution. After cooling, the content was diluted to 50 mL with distilled water and analyzed for Cd by atomic absorption spectroscopy.

Extractable Soil Cd by Other Methods: The soils used for this experiment were also extracted by 0.1M HCl (Nelson et al., 1959), 0.01M CaCl_2 (Whitten and Ritchie, 1991), DTPA (pH = 7.3) (Lindsay and Norvell, 1978), and DTPA (pH = 5.3) (Norvell, 1984).

Soil Treatments: The soils used in this study included four Cd-contaminated soils which were selected from heavy metal-contaminated agricultural lands in Taiwan and four uncontaminated soils which represented soils of the major agricultural areas in Taiwan. The properties of these soils were summarized in Table 1. The soils varied widely in pH, texture, and CEC. The Cd contamination of these soils was caused by industrial wastewater which contained Cd. To test the method's applicability to the major soils of Taiwan, the four uncontaminated soils were treated with six levels of Cd which were 0, 10, 20, 30, 40, and 50 mg Cd/kg in the form of CdCl_2 . The treated soils underwent three wetting-drying cycles at room temperature. Following these treatments, the soils were ground, passed through a 40-mesh sieve, mixed thoroughly, and stored for Cd plant uptake experiments.

RESULTS AND DISCUSSION

Preparation of Resin Membrane: To estimate the available Cd of soils, it is desirable that the extracting reagent used is not totally destructive to the soil and

TABLE 1. Physical and Chemical Properties of the Soils Studied.

Soil	Classification	pH ^c Organic Matter		CEC	Sand	Silt	Clay	Texture
		(%)		cmol(+)/kg soil	—— % ——			
Pinchen (Pc) ^a	Tropeptic Haplorthox	4.3	1.6	9.4	13	37	50	C
Chengchung (Cf)	Udifluvent	5.2	2.1	10.7	23	56	21	SiL
Erhshui (Es)	Udifluvent	7.4	4.2	8.3	16	51	33	SiCL
Taikang (Tk)	Fluventic Ustochrept	8.0	1.9	14.0	17	39	44	C
Tsaota ^b (Ts)	Typic Quartzipsamment	4.9	1.0	4.2	84	7	9	SL
Chunghsing ^b (Ce)	Typic Paleudult	5.2	1.4	8.8	22	45	33	SiC
Neuniaokang ^b (YNn)	Udifluvent	7.4	5.4	8.3	38	42	20	L
Annei ^b (An)	Udifluvent	7.7	1.0	5.1	53	35	12	SL

^a The letters in the parentheses represent the abbreviation of soil name.

^b Collected from Cd contaminated agricultural soils

^c Determined in soil : H₂O = 1:1

that the mechanism of the extraction resembles the way plants absorb Cd from the soil solution. Since the pH of Na-form of Chelex resin is about 11 (Bio-Rad Laboratories, 1987), using the commercially obtained Na-form chelating resin membrane would result in a drastic change of the soil pH, which would thus affect the ability of resins to accurately indicate the Cd availability of the soil. Therefore, the Na-form of resin membrane was transformed into Ca-form before it was used for extracting soil Cd. When the Ca-Chelex membrane was used in the experiments, the pH of equilibrating solutions were not greatly changed.

Extraction Conditions: The Ca-Chelex membrane can efficiently adsorb Cd from solutions and the adsorbed Cd can also be effectively desorbed from the membrane by 1M HCl. The recoveries of Cd by the new and regenerated Ca-Chelex membranes may reach 99 and 95%, respectively, with 15 hrs of equilibration (see Fig. 1). The high Cd recovery by the regenerated membrane makes the resin membrane reusable. It is one advantage of the chelating resin membrane method compared to other extraction methods. As 15 hrs were

FIGURE 1. The Recoveries of Cd for New and Regenerated Ca-Chelex Membranes from 5.7 mg/L Cd in 0.005 M $\text{Ca}(\text{OAc})_2$ Solutions as a Function of Time.

TABLE 2. The Langmuir Adsorption Coefficients* of Cd Adsorption by Ca-Chelex Membrane at 3 pH Levels.

pH	K (L/ μ mol)	B (μ mol/cm ²)	R
5.59	0.10	9.59	0.9950***
5.15	0.07	9.67	0.9897***
3.60	0.01	8.11	0.9895**

* Experimental data were fitted to Langmuir adsorption isotherm $C/Q = 1/KB + C/B$, where

C = equilibrium concentration of Cd in solution (μ mol/L)

Q = the amount of Cd adsorbed by unit area of membrane (μ mol/cm²)

K = a constant related to the binding strength

B = maximum amount of Cd that can be adsorbed (μ mol/cm²)

*** Significant at 0.1% level

** Significant at 1% level

sufficient for the Cd adsorption to reach equilibrium, the extraction time was set at 24 hrs for all the experiments.

Table 2 presents the coefficients of Langmuir adsorption isotherms of Cd adsorption by Ca-Chelex membrane. The coefficient K and maximum adsorption capacity, B, were higher at pH 5.59 and 5.15 than at pH 3.60. The results are characteristic for the Chelex resin whose cation exchange capacity is very low at pH < 2, then increases sharply as the pH rises from 2 to 4, and reaches a maximum at pH > 4 (Bio-Rad Laboratories, 1987). The maximum adsorption capacity of Ca-Chelex is above 8.11 μ mol Cd/cm² (0.91 mg Cd/cm²). The

concentrations of Cd in the heavily polluted soils in Taiwan range from 4.72 to 180 mg/kg (equivalent to 0.02 - 0.72 mg/4 g), and the proposed allowable level of Cd in agricultural soils is 10 mg/kg (Chen, 1992). Five cm² of the Ca-Chelex membrane will provide sufficient exchange sites for Cd which is released from 4 g of heavily Cd-contaminated soils. Therefore, the membrane we used could act as an infinite sink for extracting Cd from soils. Based on the results, the procedures described in the Materials and Methods section were adopted for estimating plant available Cd in soil.

Cadmium Extracted by Other Methods: The dry matter yields and Cd concentrations of wheat seedlings grown in these soils with various treatments are given in Table 3. The dry matter yields of treatments are not significantly different (at $P < 0.05$). The growth of wheat seedlings was not inhibited by the presence of Cd in the soils, thus the total uptake of Cd by wheat seedlings did represent soil available Cd. Extractable-soil Cd according to methods we used and amounts of Cd absorbed by wheat are listed in Table 4. Table 5 shows the correlation coefficients of Cd absorbed by wheat seedlings and extractable-soil Cd determined by the various extraction methods. It can be seen that all extraction methods used were significantly correlated with plant-uptake Cd at the 1% level. The correlation coefficients were all larger than 0.59. However, the highest correlation of Cd uptake was with resin membrane extracted soil Cd ($r = 0.97$), and the next highest with 0.01M CaCl₂ extracted Cd. Resin membrane extractable-soil Cd appears to be a better indicator of plant available Cd than Cd extracted by the other extraction methods we tested.

The poor correlations between 0.01M CaCl₂ and 0.1M HCl, DTPA (pH 7.3), and DTPA (pH 5.3) extractable-soil Cd are probably due to drastic change of pH in some tested soils when 0.1M HCl and DTPA are used. Soil pH, however, is an important factor in determining the availability of soil Cd (Bingham et al., 1979; Page et al., 1981; Alloway, 1990; Kuo, 1990), and soil Cd extraction at one pH might not reflect availability of soil Cd which was being absorbed by plant at a different pH environment. While the soil pH was not greatly affected by the use of resin membrane and 0.01M CaCl₂ as an extractant, soil pH drastically changed by the DTPA (at both pH 7.3 and pH 5.3) reagents in several soils (see Table 6). The soil pH decreased to an even larger extent when 0.1M HCl was used as the extractant. Therefore, 0.1M HCl extraction is not recommended for calcareous

TABLE 3. Dry Matter Weight and Concentration of Cd in Wheat Seedlings Grown in Different Soils with Various Treatments.

Soil ^a	Dry matter weight (g/pot)	Cd concentration (mg/kg)
Pc0	2.1 ± 0.1	ND ^b
Pc10	2.21 ± 0.06	45 ± 2
Pc20	2.21 ± 0.07	84 ± 3
Pc30	2.5 ± 0.3	120 ± 10
Pc40	2.4 ± 0.2	150 ± 20
Pc50	2.3 ± 0.2	190 ± 20
Cf0	2.3 ± 0.1	ND
Cf10	2.4 ± 0.3	23 ± 2
Cf20	2.3 ± 0.2	50 ± 8
Cf40	2.3 ± 0.1	65 ± 7
Cf50	2.6 ± 0.5	100 ± 20
Es0	2.42 ± 0.05	ND
Es10	2.25 ± 0.09	13 ± 1
Es20	2.26 ± 0.06	23 ± 2
Es30	2.2 ± 0.1	38 ± 6
Es50	2.22 ± 0.05	50 ± 20
Tk0	2.4 ± 0.2	ND
Tk10	2.3 ± 0.1	20 ± 3
Tk20	2.29 ± 0.06	26 ± 1
Tk30	2.53 ± 0.04	41 ± 3
Tk40	2.18 ± 0.07	33 ± 3
Tk50	2.47 ± 0.09	52 ± 4
Ts	2.20 ± 0.09	21 ± 3
Ce	2.5 ± 0.1	52 ± 5
YNn	2.53 ± 0.04	200 ± 30
An	2.61 ± 0.07	ND
Blank ^c	2.1 ± 0.2	ND

^a The number follows the abbreviation of soil name is the amount of Cd added in mg/kg soil.

^b < detection limit (0.7 mg/kg)

^c Grown in quartz sand without soil

soils, and the DTPA (pH 7.3) method is useful in estimating trace metal availability only by inclusion of soil pH in the interpretation of results (Baker and Amacher, 1982). The changes of soil original pH when the chelating resin membrane is used may not be as much as those when DTPA or 0.1M HCl is used. Therefore, the chelating resin membrane is a suitable metal extracting reagent for a variety of soils.

As the results of resin membrane extraction method were highly correlated with results obtained by the four other chemical extraction methods (at $P < 0.1\%$), the resin membrane method may be a good substitute for the conventional

TABLE 4. Extractable Soil Cd Determined by 6 Methods.

Soil ^a	0.1 M HCl	0.01M CaCl ₂	DTPA(pH5.3)	DTPA(pH 7.3)	Chelex Resin Membrane	Plant Extractable
----- (mg/kg soil) -----						
Pc0	ND ^b	ND ^b	ND ^c	ND ^c	ND ^b	ND ^c
Pc10	9.7 ± 0.0	8.5 ± 0.0	5.2 ± 0.0	3.7 ± 0.0	8.1 ± 0.2	1.3 ± 0.1
Pc20	19.9 ± 0.1	17.2 ± 0.1	10.6 ± 0.0	8.7 ± 0.1	16.5 ± 0.1	2.4 ± 0.2
Pc30	29.0 ± 0.1	26.3 ± 0.0	17.1 ± 0.0	12.9 ± 0.1	25.4 ± 0.1	3.7 ± 0.1
Pc40	38.6 ± 0.1	34.7 ± 0.0	22.5 ± 0.0	17.2 ± 0.1	33.2 ± 0.1	4.7 ± 0.3
Pc50	49.1 ± 0.4	44.3 ± 0.0	28.0 ± 0.1	21.5 ± 0.2	42.8 ± 0.2	5.5 ± 0.2
Cf0	ND ^b	ND ^b	ND ^c	0.09 ± 0.01	ND ^b	ND ^c
Cf10	9.7 ± 0.0	1.9 ± 0.0	9.7 ± 0.6	6.9 ± 0.0	6.3 ± 0.1	0.67 ± 0.09
Cf20	20.0 ± 0.0	4.6 ± 0.0	20.4 ± 0.0	12.7 ± 0.0	13.3 ± 0.2	1.5 ± 0.4
Cf40	33.8 ± 0.7	7.1 ± 0.0	32.7 ± 0.1	18.9 ± 0.0	22.1 ± 0.2	1.9 ± 0.3
Cf50	49.7 ± 0.1	12.7 ± 0.1	49.6 ± 0.0	25.0 ± 0.1	35 ± 1	3.4 ± 0.6
Es0	ND ^b	ND ^b	0.17 ± 0.01	0.10 ± 0.00	ND ^b	ND ^c
Es10	10.4 ± 0.1	ND ^b	8.25 ± 0.01	7.2 ± 0.0	0.9 ± 0.6	0.37 ± 0.01
Es20	20.4 ± 0.1	ND ^b	17.9 ± 0.0	14.6 ± 0.1	2.7 ± 0.1	0.67 ± 0.04
Es30	40.5 ± 0.5	0.37 ± 0.02	33.3 ± 0.2	25.5 ± 0.1	6.3 ± 0.4	1.1 ± 0.2
Es50	51.5 ± 0.0	0.65 ± 0.02	41.7 ± 0.1	33.7 ± 0.1	7.8 ± 0.3	1.5 ± 0.6
Tk0	ND ^b	ND ^b	ND ^c	ND ^c	ND ^b	ND ^c
Tk10	9.5 ± 0.0	ND ^b	7.9 ± 0.1	7.0 ± 0.0	1.1 ± 0.1	0.58 ± 0.05
Tk20	19.5 ± 0.1	ND ^b	17.7 ± 0.1	14.4 ± 0.4	2.4 ± 0.2	0.76 ± 0.05
Tk30	28.6 ± 0.0	ND ^b	26.0 ± 0.1	22.6 ± 0.3	3.7 ± 0.1	1.3 ± 0.1
Tk40	38.0 ± 0.0	0.29 ± 0.00	34.4 ± 0.0	29.3 ± 0.1	5.4 ± 0.9	0.93 ± 0.09
Tk50	48.1 ± 0.2	0.37 ± 0.00	44.2 ± 0.1	35 ± 3	6.9 ± 0.2	1.6 ± 0.1
Ts	5.0 ± 0.2	3.1 ± 0.1	3.9 ± 0.1	20.9 ± 0.4	1.4 ± 0.00	0.6 ± 0.1
Ce	25.0 ± 0.0	11.9 ± 0.1	19.0 ± 0.3	19.7 ± 0.1	9.8 ± 0.5	1.6 ± 0.1
YXn	981 ± 1	13.7 ± 0.1	440 ± 6	328 ± 6	62 ± 2	6 ± 1
An	0.75 ± 0.01	ND ^b	0.66 ± 0.02	0.33 ± 0.01	ND ^b	ND ^c

^a The number follows the abbreviation of soil name is the amount of Cd added in mg/kg soil.

^b < detection limit (0.28 mg/kg); ^c < detection limit (0.14 mg/kg)

^c < detection limit (0.056 mg/kg); ^e < detection limit (0.021 mg/kg)

TABLE 5. Correlation Coefficients of Cd Uptake by Wheat and Extractable Cd of Soils Determined by Various Extraction Methods.

	0.1 M HCl	0.01 M CaCl ₂	DTPA (pH 7.3)	DTPA (pH 5.3)	Chelex Resin Membrane
Plant	0.59**	0.84***	0.59**	0.61***	0.97***
0.1 M HCl		0.15	1.00***	1.00***	0.69***
0.01 M CaCl ₂			0.13	0.14	0.75***
DTPA(pH 7.3)				1.00***	0.68***
DTPA(pH 5.3)					0.70***

*** Significant at 0.1% level

** Significant at 1% level

TABLE 6. The Effects of Extracting Reagents on the pH of the Soil Solution.

Soil ^a	H ₂ O ^b	0.01 M CaCl ₂	0.005 M DTPA (pH7.3)	0.005 M DTPA (pH5.3)	Chelex Resin
Pc0	4.3	4.1	7.2	5.3	4.3
Pc10	4.3	4.1	7.2	5.2	4.4
Pc20	4.3	4.1	7.2	5.3	4.3
Pc30	4.3	4.1	7.2	5.2	4.4
Pc40	4.3	4.1	7.2	5.2	4.4
Pc50	4.3	4.0	7.2	5.2	4.4
Cf0	5.2	5.9	7.2	5.3	5.6
Cf10	5.2	5.9	7.3	5.3	5.6
Cf20	5.2	5.9	7.3	5.3	5.6
Cf40	5.2	6.0	7.3	5.3	5.7
Cf50	5.2	5.9	7.3	5.3	5.6
Es0	7.4	7.6	7.3	5.8	7.0
Es10	7.4	7.6	7.3	5.8	7.0
Es20	7.4	7.6	7.3	5.8	7.0
Es30	7.4	7.6	7.3	5.8	7.0
Es50	7.4	7.6	7.3	5.9	7.1
Tk0	8.0	7.9	7.3	5.7	7.1
Tk10	8.0	7.8	7.3	5.7	7.1
Tk20	8.0	7.8	7.3	5.7	7.2
Tk30	8.0	7.8	7.3	5.7	7.2
Tk40	8.0	7.8	7.3	5.7	7.2
Tk50	8.0	7.7	7.3	5.7	7.3
Ts	4.9	4.6	7.3	5.3	5.4
Ce	5.2	4.7	7.2	5.3	5.1
YNn	7.4	7.5	7.4	6.5	7.0
An	7.7	7.7	7.3	5.7	7.2

^a The number follows the abbreviation of soil name
is the amount of Cd added in mg/kg soil.

^b Determined in soil : H₂O = 1 : 1

extraction methods as resin membrane-extractable soil Cd is an equal or a better indicator of phytoavailable soil Cd.

CONCLUSION

The extractable Cd by the chelating resin membrane method had a higher correlation with Cd uptake by wheat seedlings than that obtained by the other conventional extraction methods. The chelating resin membrane method is suitable for a wide range of soils. The membrane can be regenerated and used repeatedly. In view of these advantages, the chelating resin membrane method is well suited to evaluate the quantities of plant-available Cd in soils.

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REFERENCES:

- Amer, F., D.R. Bouldin, C.A. Black, and F.R. Duke. 1955. Characterization of soil phosphorus by anion exchange resin adsorption and P-32 equilibration. *Plant Soil* 6:391-408.
- Alloway, B.J. 1990. Cadmium, pp. 100-124. IN: B.J. Alloway (ed.) *Heavy Metals in Soils*. Blackie Publishers, London, UK.
- Baker, D.E. and M.C. Amacher. 1982. Nickel, copper, zinc, and cadmium, pp. 323-334. IN: A.L. Page (ed.) *Methods of Soil Analysis: II. Chemical and Microbiological Properties*. 2nd ed. Soil Science Society of America, Madison, WI.
- Bingham, F.T., A.L. Page, G.A. Mitchell, and J.E. Strong. 1979. Effects of liming an acid soil amended with sewage sludge enriched with Cd, Cu, Ni, and Zn on yield and Cd content of wheat grain. *J. Environ. Qual.* 8:202-207.

- Bio-Rad Laboratories. 1987. Ion exchange chromatograph with chelating resins, p. 31. *IN: Guide to Ion Exchange*, Catalog number 140-9997, Bio-Rad. Richmond, CA.
- Chang, A.C., A.L. Page, J.E. Waraekke, M.R. Resketo, and T.E. Jones. 1983. Accumulation of cadmium and zinc in barely grown on sludge-treated soil. *J. Environ. Qual.* 12:391-397.
- Chen, Z.S. 1992. Metal contamination of flooded soils, rice plants, and surface waters in Asia, pp. 85-108. *IN: D.C. Adriano (ed.) Biogeochemistry of Trace Metals*. Lewis Publishers, Boca Raton, FL.
- Figura, P. and B. McDuffie. 1977. Characterization of the calcium form of Chelex-100 for trace metal studies. *Anal. Chem.* 49:1950-1953.
- Figura, P. and B. McDuffie. 1979. Use of Chelex resin for determination of labile trace metal fractions in aqueous ligand media and comparison of the method with anodic stripping voltammetry. *Anal. Chem.* 51:120-125.
- Figura, P. and B. McDuffie. 1980. Determination of labilities of soluble trace metal species in aqueous environmental samples by anodic stripping voltammetry and Chelex column and batch methods. *Anal. Chem.* 52:1433-1439.
- Jing, J. and T.J. Logan. 1991. Chelating resin method for estimation of sludge cadmium bioavailability. *Commun. Soil Sci. Plant Anal.* 22:2029-2035.
- Jing, J. and T.J. Logan. 1992. Effects of sewage sludge cadmium concentration on chemical extractability and plant uptake. *J. Environ. Qual.* 21:73-81.
- Kuo, S. 1990. Cadmium buffering capacity and accumulation in Swiss chard in some sludge-amended soils. *Soil Sci. Soc. Am. J.* 54:86-91.
- Lee, T.T. 1983. The accumulation, transformation, and utilization of phosphorus fertilizer applied in different soils under upland condition. *J. Agric. Res. China* 32:72-184.
- Lin, T.X., S.B. Ho, and K.H. Nong. 1991. The use of iron oxide-impregnated filter paper for the extraction of available phosphorus from Taiwan soils. *Plant Soil* 133:219-226.
- Lindsay, W.L. and W.A. Horvell. 1978. Development of a DTPA test for zinc, iron, manganese and copper. *Soil Sci. Soc. Am. J.* 42:421-428.
- Nelson, J.L., L.C. Boawn, and F.G. Viets, Jr. 1959. A method for assessing zinc status of soils using acid-extractable zinc and "titratable alkalinity" values. *Soil Sci.* 88:275-283.
- Norvell, W.A. 1984. Comparison of chelating agents as extractants for metals in diverse soil materials. *Soil Sci. Soc. Am. J.* 48:1285-1292.

- Page, A.L., F.T. Bingham, and A.C. Chang. 1981. Cadmium, pp. 77-110. IN: N.W. Leep (ed.) Effect of Heavy Metal Pollution on Plants: I. Effects of Trace Metals on Plant Functions. Applied Science Publishers., London, UK.
- Risser, J.A. and D.E. Baker. 1990. Testing soils for toxic metals, pp. 275-298. IN: R.L. Westerman (ed.) Soil Testing and Plant Analysis, 3rd ed. Soil Science Society of America, Madison, WI.
- Whitten, M.G. and G.S.P. Ritchie. 1991. Calcium chloride extractable cadmium as an estimate of cadmium uptake by subterranean clover. Aust. J. Soil Res. 29:215-221.