

MODELLING UPTAKE OF CADMIUM BY PLANTS IN SLUDGE-TREATED SOILS

A. K. Singh & S. B. Pandeya*

Department of Soil Science, Rajendra Agricultural University, Bihar, Pusa, 848 125, Samastipur, India

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Abstract

Laboratory and greenhouse experiments were conducted to formulate predictive models for the uptake of cadmium by Jelly bean (*Phaseolus vulgaris* L.), grown in sludge-treated soils, on the basis of soil and plant-root properties. The values of the porous system self-diffusion co-efficient (D_p) of cadmium fulvic acid complexes in soils were higher than those when Cd was applied as inorganic salts. Pot experiments were conducted with ten sewage sludge-treated old alluvium, non-calcareous, non-saline (Vertisol) soils of Patna wherein a Jelly bean crop was grown after soil treatment with 0 and 5 mg kg⁻¹ isotopically tagged and organically complexed Cd. The results indicated that the application of Cd through Cd-FA in soils did not influence the dry matter yield and root radius (r_0), root density (L_v) and half distance between the roots (r_h) of the crop, though it significantly increased the concentration of Cd in the plants and its uptake by the crop. The soil organic carbon content, cation exchange capacity, clay content, pH and EC were used to predict uptake of Cd by the crop. The root parameters and porous system self-diffusion co-efficient of Cd-FA in soils were able to predict the Cd uptake by the crop with very high levels of confidence. The modified form of the mathematical model of Baldwin et al. (1973) (Plant Soil, 38, 1973, 621–35) was found to be useful in predicting the rate of uptake of Cd by Jelly bean grown in sludge-treated soils. © 1998 Elsevier Science Ltd. All rights reserved.

Key words: Organic matter complexes, radio isotopes, fulvic acid (FA), diffusion co-efficient.

INTRODUCTION

Interest in the effects of disposal of municipal sewage-sludges on agricultural land has increased during the last decade due to their economic and environmental importance. The use of organic

wastes in crop production is cost effective, as they serve as sources of plant nutrients through recycling and modify the chemistry of most of the cations and anions so that the land becomes favourable for plant growth (Epstein *et al.*, 1976; Maiti *et al.*, 1992; Sreeramulu, 1994). Intensification of land spreading of sewage-sludge in the areas where it is produced, however, has increased concern about the potential hazards associated with increased accumulation of non-essential, potentially toxic, heavy metals in soils and their subsequent uptake by plants growing in such soils. Cadmium is one such heavy metal which has attracted great attention. Though the content of Cd in sewage-sludge of Patna (India) is 1 mg kg⁻¹, its continued disposal in soils over 100 years has increased the soil Cd concentration considerably. The organic carbon of the applied sewage-sludge mineralizes with time but the heavy metals remain accumulated in the soil with very little mobility down the profile. Transfer of these metal cations from added sewage-sludge to soils and subsequently to plants that enter the food and feed chain presents a significant health concern (Page, 1974; Chaney & Hornick, 1978; Logan & Chaney, 1983; Bidwell & Dowdy, 1987).

Fulvic acid is a low molecular weight, highly polymerized fraction of humic matter which is soluble in acidic as well as alkaline media. It is highly reactive due to its high content of acidic functional groups. Most of the properties of the humic matter in soils are attributed to this component. The complexation of metals by the polyfunctional, polynuclear, polyanion macromolecules of humic substances like fulvic acid (FA) and their interaction with the solid-phase matrices of soils with variable degrees of affinity, are known to determine the persistence and mean residence time of sludge-borne Cd in the soil solution (Sposito *et al.*, 1976; Stumm & Morgan, 1981; Stevenson, 1982; Page *et al.*, 1987). Another limiting step in determining the flux of the element to the plant roots in a soil–water–plant continuum is the rate of its trans-

*Author to whom correspondence should be addressed.

port from the bulk of the soil solution to plant roots. Most of the trace metal cations, particularly at low ambient concentrations, are delivered to the plant root surface primarily by diffusion (Barber, 1984). The naturally occurring chelating ligands are known to influence the rate of transport of metal cations through diffusion, in numerous ways (O'Connor *et al.*, 1971). The presence of sewage-derived humic matter may significantly alter the rate of transport of cadmium and this may, ultimately, play a vital role in determining the uptake of Cd by crops in sludge-treated soils. The eventual fate of sludge-borne heavy metals in soils, therefore, can best be evaluated through the determination of their effects on plant growth, and the uptake of metals by the crop grown on such soils. Regulation of safe agricultural use of city sludges and other organic wastes, moreover, requires development of some predictive models on the basis of sludge, soil and crop properties that can be used for prediction of transfer of sludge-borne heavy metals into food and feed chains. There is a lack of information on such aspects in the literature. The present paper aims to meet such requirements.

METHODS

Soils and analysis

Ten bulk surface-soil samples (0–15 cm) of old alluvium, non-calcareous, non-saline (Vertisol) soils of Patna (India) which had received sewage-sludge effluents for more than 100 years were collected for study. The sampling sites were located in the sewage-sludge disposal areas beginning at the point of discharge of the effluents to a distance of nearly 3 km away from it. The air-dried and sieved (2 mm) soils were analysed for their physical and chemical properties (Table 1). The mechanical analysis of the soils was done according to the international pipette method (Piper, 1966) and pH and EC were measured in 1:2 (soil:water) suspension. Walkely and Black's rapid titration method (Jackson, 1967) was followed for the estimation of organic carbon

contents of soils. The CEC of the soils were measured by the method of Jackson (1967). The available Cd was determined by extracting the soils with a solution containing 0.005 M DTPA, 0.01 M CaCl_2 and 0.1 M triethenolamine adjusted to pH 7.3 (Lindsay & Norvell, 1978).

Radioactive ^{115}Cd isotopes

The carrier-free radioactive ^{115}Cd in the form of $\text{Cd}(\text{NO}_3)_2$, with a half-life of 44 days, supplied by BARC, Bombay, was used for various investigations. The activity of ^{115}Cd emitting gamma-rays in soil and plant samples was measured on a gamma-ray spectrometer.

Determination of the porous system self-diffusion co-efficient (D_p)

The measurement of the porous system self-diffusion co-efficient of sludge-borne Cd in different soils was done by half-cell techniques (O'Connor *et al.*, 1971). The diffusion cell consisted of two acrylic blocks, each with diameter and depth of 2.5 cm and 1 cm, respectively. Fifty gram samples of each of the ten soils were taken in two different 100 ml beakers. Out of the two sub-samples of each soil, one received 100 ml solution containing Cd-FA (1:1) complex at the rate of 4×10^{-8} mol Cd g^{-1} and the other the same quantity of Cd-FA solution tagged with radioactive ^{115}Cd tracer at the rate of $5 \mu\text{Ci g}^{-1}$ soil. All samples were shaken for 1 h each day to attain equilibrium. In attaining equilibrium, soils were dried and wetted three times. Finally after equilibration all the soils were dried properly and ground with a mortar and pestle. The desired quantity (6.875 g) of the tagged soils, with bulk density of 1.4 kg m^{-3} , was placed into one of the diffusion half-cells and the other was filled with non-tagged soil. Water was supplied to the soils to maintain the moisture level at field capacity (0.33 bar suction). A nylon net was placed in between the two cells and both the cells were clamped so that tagged and non-tagged soils came in contact with each other and, thus, a gradient of ^{115}Cd was

Table 1. Physical and chemical properties of soils used for the various studies

Soil no.	pH	EC (dSm^{-1})	Organic carbon (%)	CEC (cmol kg^{-1})	DTPA extractable Cd (mg kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Textural class
1	7.46	1.75	2.50	23.60	0.189	52.01	28.70	8.60	SL
2	7.69	1.80	2.22	20.80	0.135	55.25	34.11	9.20	SL
3	7.77	2.00	2.13	19.65	0.078	54.93	34.20	9.40	SL
4	7.28	2.05	1.92	19.90	0.118	36.69	49.30	12.40	ZL
5	7.58	1.85	1.80	18.05	0.027	44.60	40.80	12.80	ZL
6	7.74	1.85	1.74	16.26	0.034	55.80	22.40	14.00	SL
7	7.90	1.95	1.61	14.30	0.076	34.68	45.00	18.40	ZL
8	7.87	1.92	1.47	14.01	0.064	38.16	40.50	19.21	ZL
9	7.92	1.90	1.44	10.95	0.056	23.98	52.00	21.80	ZL
10	7.35	1.75	1.32	7.70	0.032	22.20	50.00	25.30	ZL

SL, sandy loam; ZL, silty loam.

created for the diffusion. The whole system was kept in an incubator at $30 \pm 1^\circ\text{C}$ with relative humidity of approximately 100% for 20 days. After elapse of the diffusion period the cells were separated. The soil samples were digested with 50% HCl (O'Connor *et al.*, 1971). After digestion of the aliquot the volume was made to 50 ml with 1:1 HCl. Finally 2 ml of the aliquot were taken out and the activity of ^{115}Cd was measured on a gamma-ray spectrometer.

Determination of capacity factor (b)

The capacity factor for Cd in soils was determined by shaking 5 g of soil, previously equilibrated with a known activity of ^{115}Cd , with 10 ml of deionized water. The equilibrium time with intermittent shaking corresponded to the time allowed for the diffusion of Cd through half-cells. Thus all the samples were left for 20 days to be equilibrated in an incubator-shaker at $30 \pm 1^\circ\text{C}$. After equilibration, the soil suspension was centrifuged at 2500 r.p.m. and 2 ml of the aliquot were taken out for the measurement of activity of ^{115}Cd on a gamma-ray spectrometer. The capacity factor (*b*) was calculated from the amount of ^{115}Cd originally added to the soil and the activity of ^{115}Cd measured in the filtered extract using the equation,

$$b = \frac{{}^{115}\text{Cd adsorbed/cc soil} + \Phi ({}^{115}\text{Cd in solution/cc solution})}{{}^{115}\text{Cd in solution/cc solution}} \quad (1)$$

where, Φ is the volumetric water content (cc $\text{H}_2\text{O}/\text{cc}$ soil). The following transient-state equation (O'Connor *et al.*, 1971) was used for calculation of D_p and D_a in soils:

$$D_p = \frac{\pi(q/q_0)^2 \times L^2(b + \Phi)}{t} \quad (2)$$

where, D_p is the porous system self diffusion co-efficient ($\text{cm}^2 \text{s}^{-1}$), q is the amount of ^{115}Cd that diffuses from one half-cell of soil to the other in time t (cpm), q_0 is the total amount of labeled ^{115}Cd in the system (cpm), π is constant equal to 3.14, L is the length of each half-cell (cm), t is time in seconds during which the two half-cells of soil remain in contact, b is the capacity factor, and Φ is the volumetric water content of the soils.

Greenhouse experiment

The experiment was conducted in polythene-lined earthen pots in a greenhouse. Two kilogrammes of each of the ten soils were placed in each pot with three replications. To each pot, 60 mg kg^{-1} N, 40 mg kg^{-1} P_2O_5 and 40 mg kg^{-1} K_2O , in the form of urea, KH_2PO_4 and KCl solutions, respectively, were added. Three pots of each soil received carrier-free ^{115}Cd in water at the rate of $80 \mu\text{Ci}$ per 2 kg soil. In the remaining three pots of each soil sample, CdCl_2 at the rate of $0.04 \times 10^{-3} \text{ mol}$ in the form of

1:1 Cd-FA complex and tagged with ^{115}Cd ($80 \mu\text{Ci}$ per 2 kg soil) was added. The pots were sown with seeds of Jelly bean. One plant in each pot was allowed to grow after germination. Irrigation of the test crop was done every 10 days. The plants, complete with roots as far as possible, were removed from the pots at 55 days after germination by placing the soil of the pot in running water and agitating the plant-root system gently. Root and shoot portions were separated and washed thoroughly with acidified water and, finally, distilled water. Root portions were used for determination of root parameters. Then whole shoot and root samples were taken for tri-acid digestion. The final volumes of the digests were made up to 10 ml with distilled water. An aliquot of the solution was used for measuring the activity of ^{115}Cd by gamma-ray spectrometer and the concentration of Cd was measured by atomic absorption spectrophotometer. The regulations on safety for use of isotopes prescribed by BARK, India, were observed.

Evaluation of models defining rate of uptake of Cd by plants

A modification of the uptake equation developed by Baldwin *et al.* (1973), shown below, was evaluated for its suitability in predicting the rate of uptake of Cd from sludge-treated soils.

$$U = C_i b \left(1 - \exp \left\{ \frac{-2\pi\alpha A_1 r_0 L_v t}{b[1 + (\infty A_1 r_0 / D_1 \Phi f)(\ln(r_h / 1.65 r_0))]} \right\} \right) \quad (3)$$

where, soil factors: C_i is initial concentration (mol cm^{-3}) of nutrient in soil solution, b is buffer power, the change in the concentration of total labile form (adsorbed + dissolved) (mol cm^{-3} soil) per unit change in concentration of dissolved form (cm^{-3} water soil solution), A_1 is fractional area of soil solution (cm^2 water cm^{-2} soil), Φ is volumetric water content (cm^3 water cm^{-3} soil), D_1 is diffusion coefficient in solution ($\text{cm}^2 \text{s}^{-1}$); plant factors: U is uptake per unit volume of soil in time t (mol cm^{-3} soil), α is root absorbing power (uptake flux density, mol cm^{-2} root per concentration mol cm^{-3} soil solution), t is time (s), r_h is half distance between roots (cm), r_0 is root radius (cm), L_v is root density (cm root cm^{-3} soil), f is a conductivity factor (cm^2 soil cm^{-2} water), π is 3.1416.

Soils with a high adsorption capacity for specific solutes generally show higher buffer power. The buffer power was calculated from the data on adsorption of Cd-FA in the soils. The slope of the line drawn for the concentration of Cd-FA in solution and Cd-FA retained by the soils was taken as the value of b . The value of L_v was determined for roots without root hairs or micorrhizae, because their presence makes the geometry of the nutrient-absorbing system more difficult to describe quantita-

tively. L_v is equal to root length (cm) per unit volume of the soils (cm^3). The root length (l) was calculated by the equation $l = v/\pi r^2$ where, v is volume of the roots and r is radius of roots. The radius of the root was measured separately for primary, secondary and tertiary roots with the help of a microscope. Finally the values were averaged to give the mean diameter of the roots. The half distance between roots (r_h) was calculated by the method of Tylor & Klepper (1978) using Ogston's theory, by the equation $r_h = (4L_v)^{-1/2}$. The root absorbing power is equal to the uptake flux density divided by the nutrient concentration at the root surface.

The normal Cd concentration in soil solution was too small to be measured directly. So, it was measured indirectly with the help of an equation developed by Corey *et al.* (1987) in the following form:

$$M = M_T C / (K + C) \text{ or } C = MK / (M_T - M) \quad (4)$$

where, M is metal adsorbed (mg kg^{-1}), M_T is the metal adsorption capacity, computed from competitive Langmuir parameters b_1 and b_2 for the soil, K is a constant equal to the dissolved metal concentration at one half saturation of adsorption sites, and C is the equilibrium metal activity in soil solution (mg kg^{-1}).

RESULTS AND DISCUSSION

Capacity factor of Cd^{2+} and Cd-FA complexes in soils

The isotopic distribution of ^{115}Cd between the solid and solution phases at equilibrium was used to estimate the capacity factor. This in turn represents the number of units of diffusible Cd per cubic centimetre of soil needed to change its solution concentration by one unit. The capacity factors of soil for ^{115}Cd and Cd-FA complexes estimated in the present investigation are presented in Table 2. The data show that the capacity factor of Cd was, in

general, lower in soils when a Cd-FA complex was added than in those receiving CdCl_2 . A similar reduction in capacity factor due to complexation of the heavy-metal cations was reported earlier (O'Connor *et al.*, 1971; Prasad *et al.*, 1976; Gupta & Deb, 1985). The extent of reduction in the capacity factor of Cd in soils, however, was of smaller magnitude than that reported earlier by various workers for metal complexes of synthetic chelating ligands. Fulvic acid is known to have many functional groups with the capacity to donate lone pairs of electrons for complexing metal ions. Complexed metal ions are soluble at higher pH value and are less prone to surface chemical reactions with solid-phase matrices of the soils. Such protective mechanisms may be given as a reason for a decrease in the capacity factor of Cd in soils, as was observed in the present study. The low magnitude of decrease in capacity factor of soils for Cd if applied as complexes may, probably have been due to the fact that the soils contained significantly high amounts of organic carbon and the inorganic Cd species were complexes with this after their application to these soils.

Apparent and porous system self-diffusion co-efficient of Cd^{2+} and Cd-FA in soils

The values of porous system self-diffusion coefficient (D_p) and apparent diffusion coefficient (D_a) of ^{115}Cd and Cd-FA in different soils are reported in Table 2. The organically complexed Cd soils had higher values of porous system self-diffusion coefficient than did those receiving an inorganic Cd source. The reduction in capacity factor due to complexation of Cd by fulvic acid and the subsequent maintenance of higher concentrations of Cd in soil solution may, probably, have been the reasons for such phenomena. Fulvic acid is a highly oxidized, biologically stable and soluble, naturally occurring complexing agent that can complex di- and tri-valent metal ions (Schnitzer, 1977). It was interesting to note that apparent diffusion co-efficients (D_a) of Cd measured in the soils were generally higher in the case of Cd^{2+} than for the Cd-FA complex. The

Table 2. The capacity factor (b), apparent diffusion co-efficient (D_a), and porous system self diffusion co-efficient (D_p) of inorganically and organically complexed Cd in sludge-treated soils

Soil no.	Cd^{2+}			Cd-FA		
	b	D_a^a	$D_p = D_a/(b+\Phi)$	b	D_a^a	$D_p = D_a/(b+\Phi)$
1	45.60	2.96×10^{-4}	3.92×10^{-6}	39.51	2.84×10^{-4}	4.08×10^{-6}
2	41.74	2.77×10^{-4}	3.86×10^{-6}	36.16	2.92×10^{-4}	4.42×10^{-6}
3	42.69	1.23×10^{-4}	1.69×10^{-6}	30.68	1.21×10^{-4}	2.00×10^{-6}
4	38.64	5.68×10^{-5}	8.54×10^{-7}	32.80	5.65×10^{-5}	9.00×10^{-7}
5	36.89	5.04×10^{-5}	7.54×10^{-7}	41.08	5.81×10^{-4}	8.18×10^{-6}
6	46.64	5.70×10^{-5}	7.45×10^{-7}	35.77	5.45×10^{-5}	8.29×10^{-7}
7	45.60	2.81×10^{-5}	3.72×10^{-7}	42.40	2.40×10^{-5}	3.31×10^{-6}
8	39.85	2.42×10^{-5}	3.47×10^{-7}	30.05	2.40×10^{-5}	4.00×10^{-7}
9	39.87	2.24×10^{-5}	3.22×10^{-7}	36.41	2.17×10^{-7}	3.27×10^{-7}
10	38.33	4.40×10^{-6}	5.86×10^{-8}	37.18	4.05×10^{-6}	6.03×10^{-8}

^a $D_a = D_p(b+\Phi)$.

naturally occurring, polynuclear, high molecular-weight substances like FA are of large size and are, therefore, often referred to as macromolecules. Such a large molecule will naturally require higher energy for its thermal motion in soil solution. Its movement would also be expected to be slowed down considerably by the presence of colloidal particles and other ionic species in the path of its movement. It seems, therefore, quite logical that the self-diffusion co-efficient of such complexed Cd macromolecules will be lower than that of Cd^{2+} , which is of considerably smaller size (Wilkinson, 1972).

The porous system self-diffusion co-efficients of Cd in soils were positively and significantly correlated with organic carbon ($r = 0.907^{**}$), and CEC ($r = 0.785^*$), whereas they were negatively correlated with clay content of the soil ($r = 0.769^*$). A positive role of organic carbon in increasing the porous system self-diffusion co-efficient of Cd applied to the soil through inorganic sources may be due to reduction in the capacity factor. Also, the negative role of clay in the porous system self-diffusion co-efficient of Cd ions may be attributed to ion fixation by clay which may ultimately lead to a decrease in the mobility of ions caused by various physical and chemical properties (Fried & Shapiro, 1956; Singh *et al.*, 1980; Rattan & Deb, 1980).

Uptake of Cd by crops

The dry matter yield, the Cd concentration and cadmium uptake by 55-day-old Jelly bean are presented in Table 3. Though there was variation in the dry matter yield of the crop in different soils, the application of Cd-FA did not influence the yield significantly. The treatment with Cd-FA in soils increased the Cd uptake significantly over the corresponding control. Different soils were observed to provide different amounts of Cd to the plants. The

interaction effect of soils and application of Cd were also found to be statistically significant, showing that different soils behaved differently with respect to the uptake of Cd by the crop. The utilization of sewage-sludge has also been observed by Sreeramulu (1994) to increase the yield and uptake of Cd by crops. Further, the Cd uptake by plants was positively and significantly correlated with organic carbon content ($r = 0.962^{**}$), CEC ($r = 0.905^{**}$), and negatively correlated with clay content ($r = 0.841^{**}$), of the soils. The following multiple regression equation was computed to predict the uptake of Cd by Jelly bean in these soils:

Cd uptake

$$= 1.04 + 6.78\text{EC} + 2.18\text{Org.C} + 1.64\text{CEC} + 2.14\text{clay\%} \quad (R^2 = 0.93^{**})$$

This suggested that Cd uptake can be predicted with 93% confidence on the basis of EC, organic carbon, clay content and CEC of the soils. The porous system self-diffusion co-efficient (D_p) had a positive and significant correlation ($r = 0.915^{**}$) with uptake of Cd by the plant. The uptake of Cd by Jelly beans grown in Patna sludge-treated soils may, therefore, be predicted on the basis of the porous system self-diffusion co-efficient alone with the help of the following straight-line relationship:

$$\text{Cd uptake} = 1.31 \times 10^{-8} + 1.63\ln(D_p) \quad (R^2 = 0.95^{**})$$

Root parameters of Jelly bean grown in sludge-treated soils

The root parameters: radius of roots, root density and half distance between the roots, of Jelly bean grown in sludge-treated soils with or without treatment with Cd-FA are reported in Table 4. The average root radius of the crop was similar in both treated and control pots. The average values of root

Table 3. Dry matter yields, concentrations of Cd in plants and uptake of Cd by the crops grown in sludge-treated soils with or without application of ^{115}Cd tagged Cd-FA

Soil no.	Dry matter yield (g per pot)			Concentration (mg kg ⁻¹)			Uptake (μg per pot)		
	0 (mg kg ⁻¹)	5 (mg kg ⁻¹)	Mean	0 (mg kg ⁻¹)	5 (mg kg ⁻¹)	Mean	0 (mg kg ⁻¹)	5 (mg kg ⁻¹)	Mean
1	2.44	2.49	2.47	2.66	2.19	2.42	4.45	5.21	4.83
2	1.66	1.82	1.74	2.65	1.82	2.24	4.04	5.68	4.86
3	2.02	2.12	2.07	2.70	2.68	2.69	4.25	5.40	4.86
4	1.37	1.58	1.47	2.40	2.66	2.53	3.74	3.05	3.39
5	1.64	1.66	1.65	1.93	1.91	1.92	3.15	3.92	3.53
6	1.83	1.94	1.88	2.65	3.14	2.89	3.00	4.04	3.52
7	1.19	1.44	1.32	2.33	3.09	2.71	2.85	4.48	3.66
8	1.94	1.73	1.84	1.45	2.94	2.19	2.81	4.47	3.76
9	1.81	2.05	1.93	1.71	2.83	2.27	2.77	4.74	3.76
10	0.73	0.86	0.80	1.24	2.32	1.78	1.66	2.98	2.32
Mean	1.68	1.73	—	1.99	2.71	—	3.41	4.43	—
	SEM ±	CD (0.05)		SEM ±	CD (0.05)		SEM ±	CD (0.05)	
Soil	0.181	0.364		0.294	0.592		0.313	0.630	
Level	—	—		0.132	0.266		0.140	0.282	
S × L	—	—		0.416	0.837		0.444	0.894	

Table 4. Different root parameters of plants in soils with or without application of Cd-FA complexes

Soil no.	Root radius (cm) (r_0)		Mean	Root density (cm cm ⁻³ soil) (L_v)		Mean	Half distance between roots (cm) (r_h)		Mean
	0 (mg kg ⁻¹)	5 (mg kg ⁻¹)		0 (mg kg ⁻¹)	5 (mg kg ⁻¹)		0 (mg kg ⁻¹)	5 (mg kg ⁻¹)	
1	0.015	0.017	0.016	4.490	3.680	4.085	0.236	0.260	0.248
2	0.016	0.017	0.016	2.910	3.021	2.965	0.293	0.285	0.264
3	0.016	0.018	0.017	2.790	2.291	2.540	0.299	0.313	0.306
4	0.017	0.017	0.017	2.580	2.630	2.605	0.311	0.309	0.310
5	0.018	0.014	0.016	1.690	3.230	2.460	0.278	0.318	0.298
6	0.017	0.018	0.018	1.740	1.740	1.740	0.378	0.379	0.379
7	0.017	0.019	0.018	1.610	1.360	1.485	0.429	0.409	0.419
8	0.018	0.019	0.018	1.190	0.992	1.081	0.508	0.481	0.496
9	0.021	0.022	0.021	0.847	0.647	0.746	0.621	0.637	0.629
10	0.024	0.022	0.023	0.367	0.622	0.494	0.633	0.709	0.671
Mean	0.018	0.018	—	2.020	2.039	—	0.399	0.410	—
	SEM \pm	CD (0.05)		SEM \pm	CD (0.05)		SEM \pm	CD (0.05)	
Soil	0.001	0.002		0.465	0.937		0.048		0.096
Level	0.001	0.002		0.208	0.420		0.020		0.422
S \times L	0.002	0.003		0.657	1.325		0.066		0.134

density and half distance between the roots were also at par in both the control and treated pots. This indicated that application of organically complexed cadmium did not appear to have any significant impact on root parameters in Jelly bean. The Cd, being a non-essential element for the plants, may not have beneficial effects on plant growth. The levels of Cd in roots and shoots were also below the toxic limits because they did not adversely affect the growth of the crop.

On the basis of correlation studies (Table 5) it was noticed that root parameters were significantly influenced by some soil properties and, thereby, significantly influenced the uptake of Cd from the soils. Roots radius (r_0) and half distance between roots (r_h) produced positive and significant correlations with clay content of soils ($r = 0.892^{**}$, and $r = 0.962^{**}$, respectively). The root density and root length had positive and significant correlation with organic carbon, CEC, dry matter yield and uptake of Cd by the crop. The multiple regression equation given below indicated that about 95% of variation in uptake of Cd by Jelly bean could be explained on the basis of the combined effect of root radius (r_0),

root density (L_v), half distance between the roots (r_h) and porous system self-diffusion co-efficient (D_p).

$$\text{Cd uptake} = 5.17 - 1.44(r_0) + 2.38(L_v) + 1.26(r_h) + 4.84(D_p) \quad (R^2 = 0.95^{**})$$

Prediction of uptake rate of Cd by the crops with the help of the Baldwin *et al.* (1973) equation

The modified version of the mathematical model of Baldwin *et al.* (1973) (eqn (3)) was tested for its usefulness in predicting the rate of uptake of Cd by Jelly bean grown in sludge-treated soils. The fractional area (A_1) of soil solution was computed at field capacity (0.30 cm² water cm⁻² soil), whereas the value of volumetric water content (Φ) was the product of fractional area of soil solution and bulk density of the soil (i.e. 4.2 cm³ cm⁻² soil cm⁻² water). The values of conductivity factor (f) (3.0 cm² soil cm⁻² water) are the reverse of values of the fractional area. The other values (diffusion co-efficient (D_p) and root parameters) were discussed in the preceding pages. The computed values of the equilibrium concentration (C_i) ranged

Table 5. Correlation co-efficient between root parameters and soil properties

Soil and plant parameters	Root radius (cm) (r_h)	Root density (cm cm ⁻³ soil) (L_v)	Half distance between roots (cm) (r_h)	Root length (cm)
pH	-0.127	0.387	0.252	0.078
EC	-0.254	-0.265	-0.095	-0.376
Organic carbon	0.808**	0.978**	-0.882**	0.849**
CEC	-0.909**	0.940**	-0.958**	0.734*
Clay	0.892**	-0.470	0.962**	-0.732*
Yield	-0.661*	0.647	-0.496	0.720*
Uptake	-0.832**	0.938**	-0.921**	0.807**

*Significant at 5% level.

**Significant at 1% level.

Table 6. The computed values of Cd concentration in soil solution (C_i), buffer power of soils for Cd (b), Cd uptake flux density (α), and predicted and actual values of rate of uptake of Cd by the crop

Soil no.	Observed (mol cm ⁻³ soil)	Predicted (mol cm ⁻³ soil)	C_i (mol cm ⁻³)	b	α
1	3.13×10^{-10}	4.32×10^{-10}	6.79×10^{-10}	79.63	1.10×10^{-7}
2	3.09×10^{-10}	3.75×10^{-10}	6.71×10^{-10}	69.92	1.17×10^{-7}
3	2.56×10^{-10}	3.44×10^{-10}	6.66×10^{-10}	63.80	1.07×10^{-7}
4	2.34×10^{-10}	3.42×10^{-10}	5.15×10^{-10}	48.58	1.56×10^{-7}
5	1.97×10^{-10}	3.35×10^{-10}	9.27×10^{-10}	45.58	1.22×10^{-7}
6	1.88×10^{-10}	3.12×10^{-10}	3.27×10^{-10}	44.25	0.43×10^{-7}
7	1.78×10^{-10}	2.99×10^{-10}	2.67×10^{-10}	38.63	0.43×10^{-7}
8	1.76×10^{-10}	2.72×10^{-10}	2.29×10^{-10}	38.25	0.58×10^{-7}
9	1.73×10^{-10}	2.63×10^{-10}	3.34×10^{-10}	35.69	0.46×10^{-7}
10	1.04×10^{-10}	2.14×10^{-10}	2.70×10^{-10}	32.15	0.24×10^{-7}

from 2.29×10^{-10} to 6.02×10^{-10} (mol cm⁻³) (Table 6) and were within the limits reported in the literature. The organic carbon content in soil appears to control the activity of Cd in soil solution, since it produced a significant positive correlation ($r = 0.665^*$) with the activity of Cd in soil solution. The uptake co-efficient (α) determining the root absorbing power of this element by Jelly bean decreased with increase in the concentration of Cd in the soil solution. This indicated that a selective and regulated mechanism of entry of Cd into the cell sap was operative.

Finally, computation of the data was done to calculate the predicted rates of Cd uptake by Jelly bean grown in ten different soils, and these are reported, together with the corresponding observed data, in Table 6. They were in agreement with each other. The correlation co-efficient between the two sets of values was $r = 0.947^{**}$. It, therefore, appears that the Baldwin *et al.* (1973) uptake equation, with modifications as discussed, could confidently be applied to the prediction of Cd uptake by crops grown in sludge-treated soils. The model may be utilized successfully by planners and environmentalists, while formulating a policy and a plan for safe disposal of municipal wastes on agricultural land.

To make a link between the values of Cd uptake by plants as a bioindicator and corresponding DTPA-CaCl₂-Triethanolamine extractable Cd in soils, correlation co-efficients between two values were worked out. A highly significant correlation co-efficient ($r = 0.863^{**}$) was obtained from the study, indicating that the prediction of uptake of Cd by the crops grown in sludge-treated soils is possible through extraction of soils by DTPA reagent.

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