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Plant Uptake of Cadmium, Zinc, and Manganese in Soils Amended with Sewage Sludge and City Compost

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Cadmium (Cd) is an important 'toxic' heavy metal pollutant, the presence of which in agricultural soils and crops is of great concern. Naturally occurring Cd concentration in soils which ranges from 0.01 to 7 ppm (Allaway, 1968) may rise to higher concentrations as a result of aerial deposition, irrigation with contaminated water, the application of sewage-based fertilizers, pesticides containing wastes from mining, metallurgical, industrial or urban activities. Cadmium may accumulate in agricultural soils through the application of soil amendments like phosphatic fertilizers and sewage sludges which are known to contain levels of 7.3 - 170 ppm (Lisk, 1972) and <l - 3410 ppm (Alloway, 1990), respectively. Cadmium concentrations in normal plants ranged from 0.1 - 2.4 ppm (Alloway, 1990); but at higher concentration it has been shown to affect plant growth and dry matter yield adversely (Bingham et al. 1976). Differential interactions of plant micronutrients such as zinc (Zn) and manganese (Mn) with Cd in soils and plants have been reported (Page et al. 1981).

Studies on the contamination of Cd in soils and plants have so far been restricted to highly industrialised temperate regions and the availability of quantitative data on the fate of this pollutant in soils of sub-tropical and tropical regions are limited. The accelerated growth of various industries in India and the potential usage of sewage sludges and municipal composts as organic fertilizers bring into focus the question that Indian soils and soil-crop systems could be subjected to contamination with Cd. In the present paper, the plant uptake of Cd, Zn and Mn from two contrasting Indian soil types amended with sewage sludge and city compost have been investigated.

MATERIALS AND METHODS

Greenhouse pot culture experiments were conducted using two major Indian soil types, namely, a laterite soil (Ultisol) from Phondaghat, Maharashtra and a medium black soil (Vertisol-pellustert) from Hatkanangale, Maharashtra. The physicochemical characteristics of these soils are shown in Table 1. The soil amendments used were a municipal sewage sludge and a city compost obtained from Municipal Sewage Plant, Dadar, Mumbai and from

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Bombay Organic Manures Co. Ltd., Deonar, Mumbai, respectively. The concentration of 2*M* HNO_3 (total- Andersson, 1976) and diethylenetriaminepentaacetic acid (DTPA) extractable (plant-available - Lindsay and Norvell, 1978) heavy metals (Cd, Zn and Mn) in the sewage sludge and city compost are given in Table 2.

Table 1. Physicochemical characteristics of experimental soils

Characteristics	Ultisol	Vertisol
pH	5.1	8.2
Moisture equivalent (%)	30	35
Electrical conductivity (mmhos cm^{-1})	0.16	0.28
Cation exchange capacity [C mol (p^+) kg^{-1}]	10.5	60.7
Organic carbon (%)	1.36	1.32
Free $CaCO_3$ (%)	1.00	6.75
Texture	sandy loam	clay loam
Heavy metal content (μg g^{-1} soil)		
(i) Total (2*M* HNO_3 extract)		
Cd	0.3	0.5
Zn	44.0	54.0
Mn	318	1085
(ii)Available (0.005*M* DTPA extract)		
Cd	ND	ND
Zn	1.34	0.9
Mn	71.6	4.9

ND: Not detected

Table 2. Concentrations of Cd, Zn and Mn extractable by 2*M* HNO_3 and 0.005 *M* DTPA (μg g^{-1} dry wt.) and the nutrient value of sewage sludge and city compost

Heavy metal	Sewage sludge		City compost	
	HNO_3	DTPA	HNO_3	DTPA
Cd	3	0.72	1	0.78
Zn	1190	132.0	922	253.0
Mn	378	6.7	622	45.0
N %	2.1		1.2	
P_2O_5 %	1.39		0.34	
K_2O %	0.37		0.60	
Org. C %	15.2		10.4	
C/N	7.24		8.67	
pH (1:2.5)	6.2		7.7	

The above-mentioned municipal wastes were applied to one kg of the two soil types separately at doses of 0, 25, 50, 100 and 200 g kg^{-1} soil (which represent 0, 56, 112, 224 and 448 mt ha^{-1}) and mixed thoroughly in an end-over-end shaker. Each treatment was replicated four times. After one wk of incubation basal nutrients N, P_2O_5 and K_2O were applied through $(NH_4)_2SO_4$, KH_2PO_4 and K_2SO_4 at 30:20:30 mg kg soil (representing 60:40:60 kg ha, respectively). The combined fertilizer applications in this ratio contributed 0, 5.7 and 4.8 µg Cd, Zn and Mn, respectively per gram of this fertilizer (equivalent to 0, 0.5 and 0.3 µg Cd, Zn and Mn, respectively per kg soil). Two maize plants per pot were grown for 8 wks. The plant shoots were then harvested, dried at 70°C, dry matter yield noted and wet-ashed using a 5:1 HNO_3-$HClO_4$ mixture. The metal concentrations (Cd, Zn and Mn) in the acid extracts were determined using a Perkin-Elmer Model 380 atomic absorption spectrophotometer equipped with a D_2 background compensator.

Subsequent to plant harvest the soils were sampled and assayed for the DTPA extractable Cd, Zn and Mn, which represent the plant-available forms of these metals for the succeeding crop. Data were subjected to statistical analysis using either least significant difference (L.s.d.) or Duncan's multiple range tests.

RESULTS AND DISCUSSION

Data in Table 3 indicate significantly higher yields in the Vertisol with both sewage sludge and city compost amendments; whereas,

Table 3. Forage yields of maize grown on two soils amended with sewage sludge and city compost (g dry wt. pot^{-1})
Duration of growth: 8 weeks

Amendment	Sewage sludge		City compost	
dose (mt ha^{-1})	Ultisol	Vertisol	Ultisol	Vertisol
0 (soil - control)	2.38	3.34	2.38	3.34
56	3.39	5.27	2.29	4.91
112	3.52	5.08	2.43	5.08
224	3.96	5.24	1.93	6.13
448	3.30	5.16	1.22	5.24
L.s.d. (p=0.05)	NS	1.58	NS	1.67

NS: not significant

in the Ultisol no significant differences were obtained. Even at very high application rates of 224 and 448 mt ha^{-1}, no toxicity symptoms were exhibited in the maize crop. Further, levels above 56 mt ha^{-1} did not contribute to any significant yield increases. Similar enhancement in the yield of different crops due to sewage sludge addition to soil have been reported earlier (Hortenstine, 1979; Reddy and Dunn, 1984). The present findings are in agreement with earlier reports of Ham and Dowdy, 1978 and Hemphill Jr. et al. 1982, who found that sludge and compost could serve as good organic fertilizers to maximise crop yields.

Zero amendments of sewage sludge and city compost were essentially only soil controls with no addition of either sewage sludge or city compost and hence the metal concentrations are the same for a specific soil type. Significantly higher plant concentrations of Cd and Zn (Table 4) were noticed in Ultisol amended with sewage sludge at levels of 112, 224 and 448 mt ha^{-1}; whereas, Mn concentration (Table 4) decreased significantly with increasing levels of sludge amendment. In Vertisol, however, no significant differences were observed in plant Cd and Mn concentrations between the different sludge levels; but plant Zn concentration increased with increasing levels of sludge amendment.

Table 4. Concentration of Cd, Zn and Mn (μg g^{-1} dry wt) in maize shoots grown on two soils amended with sewage sludge and city compost

Amendment (mt ha^{-1})	Sewage sludge Cd	Sewage sludge Zn	Sewage sludge Mn	City compost Cd	City compost Zn	City compost Mn
Ultisol						
0*	2.3a**	41a	245c	2.3a	41a	245d
56	2.9ab	57a	46a	1.9b	50a	48a
112	3.3b	122b	55a	1.6b	61a	73b
224	4.6c	123b	49a	2.4a	91b	110c
448	4.5c	168c	85b	2.7a	125c	131c
Vertisol						
0*	2.0a	21a	60b	2.0a	21a	60b
56	2.3ab	59b	63b	2.8b	47b	40a
112	2.6b	92c	62b	2.6b	63b	45a
224	2.1a	110c	64b	2.4ab	60b	50ab
448	2.4ab	146d	39a	2.6b	105c	51ab

*Soil - control; **Values followed by the same letter within each column are not significantly different at 5% level by the Duncan's multiple range test.

Data on compost amendment (Table 4) indicate a significant enhancement in plant Zn concentration at higher levels (224, 448 mt ha^{-1}) of compost and a significant reduction in plant Mn concentration at all levels of compost amendment in Ultisol; however, no significant differences were observed in plant Cd concentration. In Vertisol, compost amendment significantly increased plant Cd and Zn concentrations, whereas, no significant differences were observed with plant Mn concentration. The levels of Cd, Zn and Mn attained in plants in the present study are comparable to those reported by MacLean et al. 1987.

The increased Cd content of plants with increased levels of sewage sludge application to Ultisol indicate that the acidic pH of Ultisol (5.1) and the sewage sludge (6.2) must have favoured conditions for increasing plant-available Cd in the maize plants. As reported by Adriano et al. 1982, by virtue of hydrogen ions released from organic matter decomposition and N mineralization, pH of the sludge-amended Ultisol might have been further lowered, thereby rendering the metals (Cd and Zn) more available for plant uptake. On the other hand, the alkaline pH of Vertisol did not favour higher Cd uptake. It is likely that in alkaline conditions of Vertisol, due to the precipitation of carbonates and hydroxides, Cd was less soluble and hence less plant-available (Lindsay, 1979). Andersson and Nilsson (1974) have reported the competition between Cd^{2+} and Ca^{2+} ions (liming effect) at root surfaces due to which there was less Cd uptake from soils. In the present study, the presence of higher percentage of free $CaCO_3$ in Vertisol (6.75% - Table 1) might be responsible for less uptake of Cd in this soil as compared to Ultisol, due to the competition between the two ions (Cd^{2+} and Ca^{2+}) and subsequent formation of $CdCO_3$ precipitate. Further, as compared to Ultisol, the adsorption capacity of Vertisol was quite high (Ramachandran and D'Souza, 1998), which could have made Cd less available for plant uptake in Vertisol. However, in the case of compost amended Vertisol, it appears that the behaviour of Cd is different from that of sewage sludge amended Vertisol as even in the alkaline pH an enhanced plant Cd concentration was noticed.

Hence, a significant enhancement in the Cd concentrations of maize plants was obtained in sewage sludge amended Ultisol due to the acidic pH and low CEC soil conditions; whereas, in the case of city compost amended Ultisol and both sewage sludge and city compost amended Vertisol the variations were not very significant which must be attributed to the chemical interactions taken place in the soil due to alkaline pH, high CEC and high $CaCO_3$ content (especially in Vertisol) and thereby making Cd in a bound form and less available for plant uptake even though Cd is not a plant nutrient.

The significant decrease in the plant concentration of Mn in sewage sludge/municipal compost amended Ultisol may be likely due to the formation of insoluble organic complexes of Mn (with the organic matter from sludge/compost). The present findings are in agreement with Hue et al. 1988, who reported that organic matter can regulate the availability of heavy metals through chelation reactions, in which the metals may form stable 5- or 6-membered ring structures with carboxyl and hydroxyl functional groups of organic aggregates, thus becoming a part of the solid phase that is unavailable to plants. The DTPA extractable Mn in Vertisol (Table 1) was quite low indicating that the sludge/compost did not play any role and hence, more or less same amount of Mn was taken up by the maize plants in both control and sludge/compost amended Vertisol.

From the above discussion it is clear that a definite soil specificity exists for the plant uptake of these metals supplied through sludge and compost and the findings are compatible with those of Baxter et al. 1983, Reddy and Dunn 1984, Chang et al. 1987, Bidwell and Dowdy 1987, and Hue et al. 1988, who reported enhanced Cd and Zn concentrations in soil and plant with sludge application. Metals in sewage sludges differ in their availability to crops depending upon soil pH, cation exchange capacity and organic matter content (Mortvedt and Giordano 1975). The lower pH and CEC of Ultisol must have influenced the greater plant accumulation of Cd and Zn. These findings are in agreement with Bingham et al. 1980, Mahler et al. 1980, and Hooda and Alloway

1994, who reported that Cd and Zn availability and uptake was higher from low pH than higher pH soils. Further, the reduced plant uptake of Mn with sludge addition is in agreement with earlier reports of Reddy and Dunn 1984.

Diethylenetriaminepentaacetic acid (DTPA) at 0.005*M* has been used as an extracting solution to monitor plant-available micronutrients like Fe, Mn, Zn and Cu (Lindsay and Norvell, 1978) and also for some other trace metals including Cd (Silviera and Sommers, 1977; Street et al. 1977) in different soils. In the present study the DTPA extractable levels of Cd, Zn and Mn in control and sludge/compost amended soils after crop harvest reported in Table 5, serve as an index of residual Cd, Zn and Mn likely to be available to the succeeding crop. Data (Table 5) further indicate that a significant increase in the plant-available Cd and Zn levels in both Ultisol and Vertisol with increased sludge/compost amendments; whereas, in the case of Mn, a significant reduction in Ultisol and a significant enhancement in Vertisol with sludge/compost amendments were noticed.

Table 5. DTPA extractable Cd, Zn and Mn ($\mu g\ g^{-1}$) from the two soils amended with sewage sludge and city compost after cropping with maize

Amendment	Sewage sludge			City compost		
(mt ha^{-1})	Cd	Zn	Mn	Cd	Zn	Mn
Ultisol						
0+	ND	1.3	71.6	ND	1.3	71.6
0++	0.01a*	1.0a	48.5d	0.01a	1.0a	48.5d
56	0.06b	9.0b	19.9c	0.03b	6.7b	25.6c
112	0.08b	17.7c	14.4bc	0.04b	11.8c	18.7b
224	0.12c	34.8d	8.3a	0.07c	22.0d	15.3ab
448	0.24d	67.0e	13.8ab	0.08d	38.6e	11.4a
Vertisol						
0+	ND	0.9	4.9	ND	0.9	4.9
0++	0.02a	0.7a	2.4a	0.02a	0.7a	2.4a
56	0.05b	10.7b	2.8ab	0.04b	7.9b	2.7a
112	0.09c	20.6c	3.2b	0.06c	14.2c	2.8a
224	0.15d	32.4d	4.2c	0.07d	28.7d	4.1b
448	0.23e	55.8e	7.1d	0.09e	38.3e	3.7b

+Soil - control before cropping; ++Soil - control after cropping;
*Values followed by the same letter within each column are not significantly different at 5% level by the Duncan's multiple range test.

A significant positive correlation was obtained (Table 6) between the DTPA extractable Cd of uncropped soil with sludge amendments and plant shoot concentration of Cd only in Ultisol. Similar findings have been reported earlier by other researchers, namely, Schauer et al. 1980, Singh 1981, Mulchi et al. 1987 and Hooda and Alloway 1994.
Significantly higher positive correlation (Table 6) between the DTPA extractable Zn and plant shoot concentration of Zn was also

observed in both soils with sludge and compost amendments. However, in the case of Mn, a significant negative correlation was obtained between the DTPA-Mn and plant shoot Mn in both soils but only with sludge amendments.

Table 6. Correlation between DTPA extractable Cd, Zn and Mn of uncropped soils and of maize shoots grown in sewage sludge and city compost amended soils

Metal	Ultisol		Vertisol	
	Sludge	Compost	Sludge	Compost
Cd	0.856*	NS	NS	NS
Zn	0.809*	0.996***	0.962**	0.954**
Mn	-0.967**	NS	-0.868*	NS

NS: not significant
*, **, ***: Significant at 10%, 1% and 0.1%, respectively.

In general, amending Vertisol with different doses of sludge/compost resulted in enhanced dry matter yield of maize plants. On the other hand, the acidic soil condition and low CEC of Ultisol favoured the high accumulation of Cd which in turn inhibited the enhancement of dry matter yield of maize plants grown in this soil. DTPA exracts of sludge/compost amended Ultisol and Vertisol can serve as a good indicator for the plant availability of heavy metals, namely, Cd, Zn and Mn in these soil types.

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