

germination time. Only slight changes in genistein concentration were noted (Table V).

The experimental results reported in this paper have demonstrated that defatting with petroleum ether and tedious cleanup steps as described by Pettersson and Kiessling (1984) can be eliminated for the determination of phytoestrogens in soybean and its processed products, thus reducing the analysis time and lowering the analysis cost. The simplified procedure reported here is suitable for use in laboratories where there is a need to assay numerous samples within short time frames.

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**Registry No.** Daidzein, 486-66-8; genistein, 446-72-0; coumestrol, 479-13-0; formononetin, 485-72-3; biochanin A, 491-80-5.

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## Heavy-Metal Absorption by Perennial Ryegrass and Swiss Chard Grown in Potted Soils Amended with Ashes from 18 Municipal Refuse Incinerators

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Perennial ryegrass (*Lolium perenne*) and swiss chard (*Beta vulgaris* L.) were grown in pots of mardin silt loam soil amended with 5 or 10% by weight of fly ash, bottom ash, or mixtures of both from 18 municipal refuse incinerators representing about one-fourth of all those operating in the United States. The ash and plant material were analyzed for total cadmium, lead, and zinc. The correlation coefficients ( $r$ ) for the concentration of cadmium, lead, and zinc in the ashes and that in the following crops were, respectively, as follows: ryegrass (first cutting), 0.9964, 0.7600, 0.9699; ryegrass (second cutting), 0.9946, 0.6895, 0.9474; swiss chard, 0.9153, 0.7609, 0.9580. Poor plant growth occurred in a few of the treatments containing ash notably higher in dissolved solids, cadmium, and zinc. The origin and association of heavy metals in refuse ash and their reactions in soils are reviewed.

Currently, there is widespread public opposition to establishing new landfill sites for disposal of municipal solid refuse owing to their unsightliness, cost of maintenance,

and potential sources of groundwater pollution. Many U.S. communities are therefore considering construction of incinerators to reduce the mass of solid waste while

offsetting maintenance costs by energy recovery. The combustible fraction of refuse may contain a wide range of discarded materials including paper products, wood, plastics, leather, rubber, and textiles as well as food and yard wastes. Noncombustibles may include glass, ceramics, ferrous and nonferrous metals, soil, and rock. In some locations, refuse is coincinerated with sewage sludge or with coal in power plants. Animal carcasses, organs, and organic wastes from hospitals, laboratories, or pounds are normally burned in incinerators specifically designed for that purpose.

Disposal of the resulting incinerator fly and bottom ash is presently of concern since they may contain high concentrations of a number of toxic elements including arsenic, cadmium, chromium, copper, mercury, manganese, nickel, lead, selenium, zinc, and others (Norton et al., 1986; Taylor et al., 1985; Wadge and Hutton, 1987; Wadge et al., 1986; Hrudey et al., 1974; Gallorini et al., 1980) as well as toxic organic compounds. Disposal of such ash in landfills could result in accumulation of toxic elements in cover crops such as grass. The purpose of this study was to determine the extent of uptake of several elements by a grass and a leafy vegetable cultured in potted soils amended with refuse incinerator ash from a number of locations in the United States.

## EXPERIMENTAL SECTION

About 15 kg of freshly produced ash was obtained from each of 18 municipal solid waste incinerators throughout the United States in 1987. The ashes received were either bottom ash, fly ash, or a mixture of the two, depending on the particular ash disposal method of each facility. (If the concentrations of specific toxicants in the fly ash are too high for landfilling, it is legal in operating a refuse incinerator to mix the latter with an appropriate quantity of bottom ash and then dispose of the composite in a landfill.) The total material was air-dried at room temperature. Fly ashes were mixed by tumbling. In the case of samples containing bottom ash, large stones, glass, and metal objects (discarded tools, utensils, etc.) were first discarded. The remaining material was pulverized to pass through a 5-mesh screen and then reduced to a fine powdery consistency in a hammermill. This material was then mixed. Each of the ashes were then subsampled for analysis.

Mardin silt loam (coarse-loamy, mixed, mesic typic fragiochrepts) at three pH values was used for the plant growth studies. Several hundred pounds of the original soil, pH 5.6 (cation-exchange capacity = 9.1 mequiv/100 g) was thoroughly mixed by repeated quartering. It was then divided into thirds. Powdered sulfur was mixed into one-third and lime into another one-third, and the soils were kept moist for 6 months until soil pHs of 4.8 and 7.3 were attained, respectively. The remaining one-third was kept at its original pH of 5.6. Soil pH was measured by the method of Peech et al. (1953).

Specific ashes and soils were mixed in a cement mixer in the dry state and poured into plastic pots 15 cm in both diameter and height and containing drainage holes. Table I lists the specific ash-soil combinations used for plant growth and the final pH of the resulting mixtures. These soils were chosen in order that particular ashes could be added to specific soils at 5 or 10% by weight to attain a pH satisfactory for crop growth. Newly produced refuse ashes are typically high in pH (Vogg, 1987). In May 1988 the pots were seeded in the greenhouse with 1 g of "Bison" perennial ryegrass (*Lolium perenne*) or "Fordhook Giant" swiss chard (*Beta vulgaris* L.), the latter crop being thinned to two plants per pot. Plants grown in the particular soil without ash served as controls. Each treatment was replicated five times, and the pots were arranged in a randomized block design. Each pot was fertilized biweekly with 200 mL of a solution containing, respectively, 449, 209, and 423 ppm of N, P, and K. All plants were watered as required. The temperature in the greenhouse was maintained between 18 and 24 °C with evaporative cooling pads. Relative humidity ranged from 65 to 70% and

**Table I.** pH of the Ash, Soil, and Mixture Used for Plant Growth

ash code	ash type	% ash in soil	ash pH	soil pH	ash-soil pH
A	FA <sup>a</sup>	10	7.3	5.6	6.2
B	FA <sup>a</sup>	5	12.5	4.8	7.2
C	FA <sup>a</sup>	10	4.2	7.3	7.1
D	FA <sup>a</sup>	10	8.4	5.6	6.2
E	FA <sup>a</sup>	10	10.6	4.8	6.4
F	BA <sup>b</sup>	10	11.3	4.8	7.1
G	BA <sup>b</sup>	10	7.9	5.6	6.7
H	BA <sup>b</sup>	5	12.5	4.8	7.2
I	BA <sup>b</sup>	10	9.5	4.8	6.9
J	BA <sup>b</sup>	10	7.4	5.6	6.1
K	BA <sup>b</sup>	10	9.5	4.8	7.1
L	BA <sup>b</sup>	10	7.9	7.3	7.3
M	FA-BA <sup>c</sup>	10	8.2	5.6	6.5
N	FA-BA <sup>c</sup>	5	8.4	5.6	6.3
O	FA-BA <sup>c</sup>	10	8.7	5.6	6.7
P	FA-BA <sup>c</sup>	10	9.3	4.8	6.7
Q	FA-BA <sup>c</sup>	10	9.1	5.6	6.7
R	FA-BA <sup>c</sup>	10	9.7	4.8	7.1
S	FA-BA <sup>c</sup>	10	10.2	4.8	6.7
T	FA-BA <sup>c</sup>	10	9.8	4.8	7.2

<sup>a</sup> Fly ash. <sup>b</sup> Bottom ash. <sup>c</sup> Fly ash-bottom ash mixture.

day length from 15 to 16 h. Light intensity ranged from 9496 to 14883 Langleys between May and September.

A first and second cutting of ryegrass was taken each time the grass was about 20 cm in height. The swiss chard was harvested twice when the plants were about 20 cm in height, and the two cuttings were combined prior to heavy-metal analysis. The plant material was air-dried, milled through a 16-mesh screen, mixed by tumbling, and subsampled for heavy-metal analysis. Nitrogen was determined in the ashes and soil by the Kjeldahl method. Organic matter was determined in the ashes and soil by dry-ashing at 500 °C overnight and weighing the residue. Total dissolved solids were determined in the ashes by Soxhlet extraction with distilled water, evaporation of the water, and weighing. The ash, soil, and plant samples were wet-ashed with nitric and perchloric acids (Gorsuch, 1970). Phosphorus and potassium were determined in the acid digests of the ashes and soil by inductively coupled plasma emission spectrometry. Cadmium, lead, and zinc were determined in the digests by conventional stripping voltammetry (Gajan and Larry, 1972). The coefficient of correlation (*r*) was calculated to test the relation between the concentrations of each of the latter heavy metals in the plants and those in the respective ashes on which they were grown (Table V).

## RESULTS AND DISCUSSION

The total concentrations of plant nutrient elements, organic matter, total dissolved solids, and heavy metals in the refuse ash and soil are shown in Table II. On the basis of the organic matter content of several of the ashes, it is obvious that incineration was grossly incomplete. Whereas the nitrogen content of the ash closely paralleled that of organic matter, the behavior and fate of most elements during refuse incineration are poorly understood and can only be generalized. The elemental composition of refuse ash depends on the composition of the refuse, which is highly variable, the type of incinerator and conditions during combustion. Elements such as zinc are found largely in the bottom ash while more volatile elements such as cadmium and lead tend to be vaporized in the combustion zone and condense on fine particles to an extent inversely proportional to particle size (Wadge et al., 1986). The particles then either are trapped as fly ash or escape to the atmosphere as suspended particulates (Greenberg et al., 1978; Brunner and Mönch, 1986). Magazine paper is a notable source of lead and zinc (Campbell, 1976). A major source of chlorine in refuse

**Table II. Total Concentrations of N, P, K, Organic Matter, Total Dissolved Solids, and Heavy Metals in the Refuse Ash and Soil**

ash code	% dry wt					ppm dry wt		
	N	P	K	OM <sup>a</sup>	TDS <sup>b</sup>	Cd	Pb	Zn
A	nd <sup>c</sup>	0.53	2.71	1.74	7.03	185	5334	10039
B	nd	0.34	1.01	2.11	0.78	17.9	921	1546
C	nd	0.37	1.71	7.42	4.51	16.5	375	1393
D	nd	0.77	7.83	7.34	21.49	477	2134	14301
E	nd	0.03	2.21	2.08	0.80	1.0	56	75
F	nd	0.32	1.14	3.11	0.76	4.5	1619	3728
G	0.38	0.31	0.78	29.19	2.63	15.6	5471	4557
H	nd	0.35	1.24	4.66	2.07	18.4	7959	5937
I	0.25	0.48	1.42	14.50	2.08	7.8	2740	4217
J	0.10	0.42	2.24	28.67	12.17	442	5123	36125
K	0.14	0.44	0.79	20.00	2.78	4.6	983	4218
L	nd	0.60	1.92	3.62	1.57	124	6248	8861
M	0.89	0.15	0.42	72.06	4.41	17.4	527	7486
N	0.45	0.15	0.53	73.97	1.58	6.4	684	3012
O	0.16	0.22	0.57	42.92	3.11	1.0	2021	1723
P	0.17	0.45	0.87	9.51	1.11	28.3	3348	3213
Q	0.24	0.31	0.89	32.87	2.47	35.5	3216	3987
R	0.03	0.40	0.74	9.50	1.36	3.0	624	3053
S	nd	0.44	1.62	1.64	0.51	1.0	108	632
T	nd	0.24	0.54	8.28	1.74	37.0	2723	5029
Mardin soil	3.9	3 <sup>d</sup>	45 <sup>d</sup>	5.50		0.21	18.6	96

<sup>a</sup> Organic matter. <sup>b</sup> Total dissolved solids. <sup>c</sup> Not detectable, i.e., less than 0.1% dry weight. <sup>d</sup> Kilogram/hectare available.

**Table III. Concentrations of Heavy Metals in Two Cuttings of Perennial Ryegrass Grown in Potted Soil Amended with Refuse Incinerator Ash**

ash code	ash type	ppm dry wt, first cutting			ppm dry wt, second cutting		
		cadmium	lead	zinc	cadmium	lead	zinc
A	FA <sup>a</sup>	4.92 ± 0.46 <sup>b</sup>	10.8 ± 1.1	230.9 ± 3.8	5.59 ± 1.10	10.7 ± 0.81	237.5 ± 12.1
B	FA	0.26 ± 0.01	0.91 ± 0.23	52.9 ± 2.0	0.39 ± 0.03	0.86 ± 0.11	54.7 ± 2.0
C	FA	0.73 ± 0.20	1.99 ± 0.38	71.3 ± 3.7	0.61 ± 0.06	1.24 ± 0.01	80.9 ± 4.9
D	FA	10.7 ± 0.6	2.97 ± 0.55	247.9 ± 8.0	16.6 ± 0.7	3.84 ± 0.27	505.3 ± 36.1
E	FA	0.08 ± 0.01	0.75 ± 0.09	47.9 ± 3.9	0.11 ± 0.01	1.28 ± 0.03	39.4 ± 1.5
F	BA <sup>c</sup>	0.14 ± 0.01	1.27 ± 0.14	117.5 ± 6.0	0.31 ± 0.03	1.12 ± 0.07	146.0 ± 4.7
G	BA	0.51 ± 0.06	7.82 ± 1.42	148.5 ± 7.8	1.03 ± 0.12	9.79 ± 0.97	235.7 ± 15.8
H	BA	0.12 ± 0.03	2.48 ± 0.21	128.4 ± 4.9	0.21 ± 0.02	3.15 ± 0.09	165.6 ± 9.3
I	BA	0.22 ± 0.09	0.94 ± 0.81	155.1 ± 4.3	0.25 ± 0.03	1.14 ± 0.06	217.4 ± 15.8
J	BA	11.1 ± 0.9	18.4 ± 1.4	502.3 ± 20.3	16.0 ± 1.0	31.2 ± 2.4	806.3 ± 43.1
K	BA	0.10 ± 0.01	0.90 ± 0.05	108.8 ± 3.5	0.17 ± 0.01	0.93 ± 0.08	181.9 ± 5.0
L	BA	2.52 ± 0.12	7.39 ± 0.48	190.7 ± 6.5	2.53 ± 0.13	9.47 ± 0.50	202.6 ± 15.2
M	FA-BA <sup>d</sup>	0.17 ± 0.02	1.57 ± 0.17	125.7 ± 5.2	0.18 ± 0.01	0.63 ± 0.06	116.8 ± 4.1
N	FA-BA	0.20 ± 0.02	2.82 ± 0.27	83.1 ± 4.8	0.34 ± 0.02	0.67 ± 0.09	103.4 ± 8.5
O	FA-BA	0.13 ± 0.01	1.95 ± 0.40	78.5 ± 4.8	0.37 ± 0.03	1.07 ± 0.04	118.9 ± 3.8
P	FA-BA	0.39 ± 0.03	2.49 ± 0.20	160.9 ± 6.8	0.97 ± 0.05	5.37 ± 0.29	234.1 ± 9.8
Q	FA-BA	0.75 ± 0.03	1.76 ± 0.28	96.4 ± 8.8	1.15 ± 0.10	1.54 ± 0.15	112.7 ± 5.9
R	FA-BA	0.11 ± 0.01	0.86 ± 0.13	91.4 ± 4.6	0.16 ± 0.01	0.74 ± 0.08	116.9 ± 5.3
S	FA-BA	0.07 ± 0.01	0.67 ± 0.09	58.9 ± 1.0	0.11 ± 0.01	0.65 ± 0.03	71.4 ± 1.0
T	FA-BA	0.84 ± 0.06	2.12 ± 0.28	168.5 ± 13.3	1.10 ± 0.07	2.40 ± 0.30	239.1 ± 17.0
Mardin pH 4.8		0.12 ± 0.02	0.86 ± 0.12	41.9 ± 3.4	0.20 ± 0.02	0.65 ± 0.07	37.7 ± 0.8
Mardin pH 5.6		0.14 ± 0.02	0.60 ± 0.06	46.6 ± 2.4	0.23 ± 0.02	0.47 ± 0.02	40.9 ± 2.0
Mardin pH 7.3		0.11 ± 0.01	1.15 ± 0.23	49.6 ± 5.2	0.19 ± 0.04	1.01 ± 0.10	48.0 ± 1.4

<sup>a</sup> Fly ash. <sup>b</sup> Mean ± standard error of five replicated pots. <sup>c</sup> Bottom ash. <sup>d</sup> Fly ash-bottom ash mixture.

is poly(vinyl chloride) (Brunner and Ernst, 1986), which, when released upon incineration, not only contributes to the salt content of the ash but may lead to formation of volatile chlorides of elements such as cadmium, lead, and zinc, which may greatly increase their presence in fly ash (Greenberg et al., 1978). Vaporization of some elements may be enhanced if they are dispersed in combustible material such as additives to plastics and therefore vaporized at least for short intervals as the material burns. As pointed out by the latter authors, reactions during refuse incineration are very complex.

Other factors may also affect the extent of vaporization of toxic elements. The higher the calorific value of the refuse, the greater will be the vaporization and emission of cadmium, lead, and zinc. The moisture content of the fuel, largely determined by its content of food and yard wastes, can greatly affect the efficiency of fly ash

collection by electrostatic precipitators (Brunner and Mönch, 1986). The presence of noncombustible material in the fuel may also contribute to the load of metals in the fly ash (Greenberg et al., 1978; Law et al., 1978).

The crops in most treatments grew well and showed no external symptoms of toxicity with the exception of perennial ryegrass in treatment M and swiss chard in treatments D, J, and M, which exhibited some yellowing and stunted growth. Ashes D and J were notably high in cadmium, lead, zinc, and total dissolved solids. Swiss chard from treatments D and J were notably high in cadmium and zinc. Giordano et al. (1983) attributed phytotoxicity in plants grown on soils amended with refuse ash to the high salt content of the ash rather than a specific metal.

The concentrations of the metals in the first and second cuttings of perennial ryegrass grown on the refuse

**Table IV. Concentration of Heavy Metals in Swiss Chard Grown in Potted Soil Amended with Refuse Incinerator Ash**

ash code	ash type	ppm dry weight		
		cadmium	lead	zinc
A	FA <sup>a</sup>	31.5 ± 3.4 <sup>b</sup>	5.36 ± 0.32	264.6 ± 10.6
B	FA	0.63 ± 0.05	1.01 ± 0.10	35.6 ± 1.6
C	FA	1.67 ± 0.08	1.61 ± 0.17	56.8 ± 4.2
D	FA	64.4 ± 4.0	2.32 ± 0.18	262.3 ± 32.0
E	FA	0.60 ± 0.03	1.98 ± 0.09	60.1 ± 4.8
F	BA <sup>c</sup>	0.38 ± 0.05	1.26 ± 0.07	102.8 ± 9.1
G	BA	2.02 ± 0.10	2.58 ± 0.18	111.9 ± 7.8
H	BA	0.38 ± 0.03	1.86 ± 0.10	163.4 ± 10.0
I	BA	0.59 ± 0.09	1.09 ± 0.07	270.8 ± 18.8
J	BA	136.3 ± 8.6	10.2 ± 2.3	1060.0 ± 97
K	BA	0.32 ± 0.04	0.74 ± 0.08	201.9 ± 26.1
L	BA	18.0 ± 2.0	10.9 ± 0.64	210.9 ± 26.5
M	FA-BA <sup>d</sup>	0.96 ± 0.06	1.25 ± 0.12	174.1 ± 8.2
N	FA-BA	0.75 ± 0.10	0.63 ± 0.02	70.2 ± 8.1
O	FA-BA	1.06 ± 0.10	0.91 ± 0.05	61.1 ± 5.4
P	FA-BA	3.63 ± 0.33	2.25 ± 0.09	236.9 ± 16.8
Q	FA-BA	2.48 ± 0.17	1.41 ± 0.09	121.7 ± 3.9
R	FA-BA	0.35 ± 0.03	0.66 ± 0.05	84.4 ± 7.0
S	FA-BA	0.15 ± 0.02	0.69 ± 0.10	52.3 ± 4.6
T	FA-BA	3.41 ± 0.31	1.50 ± 0.13	221.2 ± 14.2
Mardin pH 4.8		0.56 ± 0.04	0.48 ± 0.03	66.9 ± 4.6
Mardin pH 5.6		0.93 ± 0.08	0.92 ± 0.09	48.8 ± 0.9
Mardin pH 7.3		0.15 ± 0.02	0.69 ± 0.07	28.1 ± 2.3

<sup>a</sup> Fly ash. <sup>b</sup> Mean ± standard error of five replicated pots. <sup>c</sup> Bottom ash. <sup>d</sup> Fly ash-bottom ash mixture.

**Table V. Correlation Coefficients for Heavy Metal Concentration in Crops and in the Refuse Ash They Were Grown in**

crop	<i>r</i> values <sup>a</sup>		
	cadmium	lead	zinc
ryegrass (first cutting)	0.9964	0.7600	0.9699
ryegrass (second cutting)	0.9946	0.6895	0.9474
swiss chard	0.9153	0.7609	0.9580

<sup>a</sup> Values for all treatments containing 10% ash in soil and controls; i.e., treatments B, H, and N containing 5% ash (Table I) are not included in the correlation. *p* < 0.01 for all correlations.

ash-soil mixture are given in Table III. In the majority of treatments, including the controls, the second cutting of the plants showed higher concentrations of cadmium and zinc than the first cutting in the respective treatment. This was only true in some cases with lead. Continuous growth and proliferation of roots during the second growth of the ryegrass with more complete absorption of heavy metals during this period may partially account for the higher observed metal content in the second cutting. Lead is fixed in soil by clays, iron oxides, and association with organic matter.

Table IV lists the concentrations of the metals in the ashes and correspondingly grown swiss chard. Swiss chard consistently absorbed higher concentrations of cadmium than the first cutting of ryegrass. Leafy vegetables are well-known accumulators of cadmium (Furr et al., 1981). The correlation coefficients for the total heavy-metal concentrations in the crops and in the refuse ashes they were grown in are given in Table V. The highest degree of correlation was shown for cadmium and zinc. Prior to subdividing the ashes used in this study in a hammermill, pieces of metallic lead possibly from soldering or use in plumbing were found in various of them as received. It was not possible to remove all of these prior to milling. This may partially explain the lower correla-

tion between the total concentrations of lead in the plants and those in the ashes. The latter metallic lead would dissolve during acid digestion and be included in the ash analysis but would be virtually insoluble in soil solution for absorption by plant roots. The possible presence of an appreciable portion of the lead in refuse as the metal is indicated in the data of Gregson et al. (1988) showing that over half of the lead in refuse was soluble in nitric acid.

Other workers have reported on the absorption of metal by plants grown on refuse ash amended soil. Giordano et al. (1983) grew corn and swiss chard in potted soil to which was added 30% (w/w) refuse bottom ash as a surface, middepth, or a totally mixed amendment. They also included pots of soil containing 15% refuse fly ash as a surface amendment. The plants absorbed relatively high concentrations of cadmium and lead, the uptake of which was believed to be promoted by chloride complexation of the metals [owing to the high chloride content of the ashes (10–12%)], thus increasing their mobility in the soil. Bingham et al. (1983) have reported an increase in the cadmium content of swiss chard leaves as a result of chloride treatment of the soil. A major cationic species of cadmium in soil solutions from polluted soils has been reported to be CdCl<sup>+</sup> (Tills and Alloway, 1983). Interestingly, ashes A and J showed high concentrations of total dissolved solids (TDS) (Table II) and also elevated levels of cadmium and lead in ryegrass and swiss chard, but the total contents of these metals in those respective ashes were also relatively high. However, swiss chard grown on ash L was also high in lead, and this ash was not notably high in TDS. The content of chloride in the TDS was not determined. Wadge and Hutton (1986) grew barley and cabbage in potted soils containing 10–40% (w/w) refuse incinerator fly ash. The crops absorbed significantly elevated levels of cadmium and lead with cabbage grown on 20% ash-amended soil containing 146 times the concentration of cadmium in the controls.

The forms of heavy metals in refuse incinerator ashes are speculative. It is presumed that metals in fly ash may be combined in a number of forms including readily exchangeable, precipitated or coprecipitated with surface carbonates or oxides, bound or adsorbed to iron and manganese oxides, organically complexed with or adsorbed to sulfur, or present in mineral lattices (Wadge and Hutton, 1987). With use of specific extractants favoring removal of elements in any of one of the latter associations, it was shown that cadmium and lead in refuse fly ash were mainly associated with the exchangeable fraction whereas in coal fly ash they were mostly present in mineral lattices. These metals are typically much higher in concentration and more water-soluble in refuse fly ash than in that of coal. The high pH of some newly produced refuse ashes will initially inhibit dissolution of such metals, however (Vogg, 1987). Plants grown on coal fly ashes are typically higher in elements such as selenium and boron than those cultured on refuse ashes.

The reactions of heavy metals and other elements in refuse ashes when the latter materials are incorporated in soils have been studied little. Cadmium in refuse incinerator slag leachates have been reported to be rapidly sorbed by soil (Christensen, 1985). However, other metals typically present in refuse ashes such as chromium, cobalt, copper, lead, nickel, and zinc can compete with cadmium in this regard (Christensen, 1987). Organic matter additions to soil increase its cation-exchange capacity and thereby may decrease absorption of cadmium by plants (Haghiri, 1974). Cadmium forms only weak com-

plexes with organic substances, which contribute to its mobility at about pH 8 (Esser and Bassam, 1981). Such reactions might presumably be of importance if poorly incinerated refuse ashes having high organic matter content and an alkaline pH are used as soil amendments. Lead is fixed by iron oxides and soil humic acids (Hildebrand and Blum, 1974a,b). It forms stable organic complexes as soil pH increases (Gregson and Alloway, 1984), and lead uptake by plants has been reported to decrease as soil pH, cation-exchange capacity, and available phosphorus increase (Miller et al., 1975a,b; Cox and Rains, 1972).

Owing to their typically high content of heavy metals and other toxic elements and organics, refuse incinerator ashes will probably never be intentionally used as amendments to agricultural soils. Refuse ash landfills are typically capped with about 0.75 m of soil. This means that, initially, only deep-rooted plants may absorb heavy metals. Eventually, however, earthworm and other soil faunal activity could lead to incorporation of the ash into the above soil layers with resultant uptake of such metals by shallow-rooted plants. Research concerning the absorption by plants of elements from refuse ash amended soil is just beginning. However, as in the case of sewage sludge, it is probable that cadmium will be the element of most concern owing to its prevalence in such ashes, its mobility and toxicity.

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**Registry No.** Cd, 7440-43-9; Pb, 7439-92-1; Zn, 7440-66-6.

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