EFFECT OF SEWAGE SLUDGE ON NUTRIENT AND TOXIC METAL CONTENT OF SOIL AND SELECTED CROPS GROWN ON TROPICAL SOILS

by Nancy Cavallaro, Ph.D.

and

José Villarrubia, Ph.D.
Department of Agronomy and Soils
University of Puerto Rico
Mayagüez, Puerto Rico

Project No. 3
Grant Agreement No. 14-08-0001-G1611

FINAL TECHNICAL REPORT
TO
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

The work on which this report is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Research and Development Act of (P.L. 98-242).

August 30, 1989

TABLE OF CONTENTS

LIST OF TABLES

List of Tables (con'd)

Introduction

The use of sewage sludge as a soil amendment is an attractive idea for the disposal of this waste and considerable research has been done on the subject in the United States, Canada and Europe. The results have been quite variable depending on the nature of the sludge, soil, crop and environment. In studies where no toxic effects were found from the sludge, many crops have been shown to respond well to this material due to its content of primary plant nutrients and other interactions with the soil (Sommers and Sutton, 1980, McCoy et al 1986, Mellbye, 1982) although a plateau or decrease in yield is sometimes reached with increasing rates of application (Higgins, 1984, Heil and Barbarick, 1989). In order to use this material effectively, it is necessary to evaluate its potential for supplying plant nutrients or for affecting the availability of nutrients already in the soil. At the same time, toxic metals which may be present in the sludge need to be quantified and their effects evaluated in terms of possible soil and groundwater pollution, plant growth, and accumulation in plant parts consumed by organisms higher in the food chain in order to establish loading rates for the sludge or the metals.

The interaction of sludge with the soil, which largely governs crop uptake and metal movement, depends on many specific factors in the sludge and soil and environment as well as on cultural practices used so that total content of metals in sludge is not a reliable indicator of metal absorption by plants. Such soil characteristics as pH, cation exchange capacity, organic matter content, and hydrous aluminum, iron and manganese oxide surface area play an important role in determining tolerance levels for heavy metals (Bingham et al, 1979; Cavallaro and McBride, 1980 and 1984; CAST, 1980; Iwai, et al, 1975; Maclean, 1976;, Overcash and Pal, 1979). Thus it is necessary to evaluate the potential hazards and benefits associated with sludge application to crop land for the specific soil and environmental conditions present in Puerto Rico.

The objectives of this study were to determine the effects of sewage sludge applied to soils on 1) the concentration of nutrients and toxic metals in edible and non-edible portions of plants grown on these soils, 2) the concentrations of available nutrients and toxic metals in the soils, and 3) the distribution of the different forms of metals in the soils. It is an extension to two new sites and soil types, of a similar study done two years earlier.

Materials and methods:

Two sites were selected for this study: one on an Oxisol (Coto clay) in the semi-humid northwestern coast of Puerto Rico, and another on a Vertisol (Fraternidad) of the fertile Lajas Valley in the semi-arid southwestern part of the island. The average values for some soil characteristics are given in Table 1.

Three field experiments were established, one on the Coto where eggplant (Solanum melongena) was planted, and two on the Fraternidad where the test crops were pigeon pea (Cajanus cajans L). Five treatments were applied to 4m X 4m plots for the eggplant and 6m X 6m plots for the sorghum and pigeon pea in a randomized complete block design.

The five treatments were 0, 8, 16 and 24 Mg ha^{-1} of aged Ponce Municipal sewage sludge plus a treatment with a complete fertilizer, including lime on the acid site (Coto). Treatments were incorporatied to a depth of 10 to 15 cm shortly after application. No other amendments were added. After the initial pre-plant herbicide, weeding was accomplished by hand cultivation. Adequate moisture was maintained by overhead irrigation.

Samples were taken at flowering of the youngest fully expanded leaves for the pigeon pea and eggplant and just before flowering of the sixth and seventh leaves for the sorghum. Grain and leaf samples were taken of the sorghum at harvest for the first crop and only leaf samples were taken at harvest of the ratoon crop. Yield of sorghum grain could not be adequately determined due to heavy losses to birds so only forage yields were measured for this crop. Eggplants were harvested four times and after the final harvest, whole plants were cut and weighed to get above-ground biomass yield. Several eggplants were sectioned from each plot at each harvest and the middle sections were used for analysis. Two crops of pigeon peas were harvested and subsamples of the grain from each plot were used for analysis. All plant tissue was dried at 70C for 24 hours in an air convection oven, and then ground in a stainless steel mill.

Dried tissue samples and three replicate sludge samples were ashed in a muffle furnace at 500C overnight. Samples were then baked with hydrochloric acid for two hours to dehydrate the silica in order to eliminate interferences in the phosphorus determination and minimize loss of heavy metals due to adsorption. All metals were determined by atomic absorption (Ca, Mg, K, Na, Cd, Cu, Co, Cr, Fe, Mn, Ni, Pb, and Zn), and phosphorus by the colorimetric vanadomolybdate procedure (Greweling, 1976).

Soil samples from depths of 0-15cm and 15-30cm were taken from each plot before applying the treatments, two weeks following treatment application, and at the final harvest from the pigeon pea and eggplant sites, and at each harvest for the sorghum site. Samples were air-dried and ground to pass a 20 mesh seive. For the metal fractionation study, composite samples were prepared by thoroughly mixing equal amounts of the replicate plot samples for each treatment for each site.

Soils were analyzed for pH (1:2 water), exchangeable bases (1N ammonium acetate, pH 7), available phosphorus (Bray P-1), and Mehlich 3 extractable Ca, Mg, K, Na, Cd, Cu, Co, Cr, Fe, Mn, Ni, Pb, and Zn. All metals were determined by atomic absorption. Fractionation of the metals in the composite samples was done according to the procedure developed by Shuman, 1985.

Results and Discussion:

1. Sludge analysis:

Table 2 gives the pH and total amounts of selected nutrients and heavy metal in the sludge. It is moderately high in phosphorus compared to other sludges and organic amendments, although the Bray-1 extractable P is considerably less. The sludge is also high in the micronutrients iron, zinc and copper. For the toxic metals, the amounts added in the treatments were only significant for lead and nickel (Table 3) although both are below levels which would be expected to cause an increase in leaf concentrations (Mitchel, et al, 1978; Overcash and Pal, 1979).

2. Effect of Sludge on yield:

Yields of all three crops including both harvests of sorghum are given in Table 4. In all cases no statistically significant differences were detected even between the control and complete fertilizer treatment. Thus on preliminary analysis we could say that the sludge applications did not effect yields but on the other hand, produced as good yields as the recommended complete fertilizer treatment. This might be expected for the crops planted on the Vertisol which is a very fertile soil which often shows little response to fertilizer but was not expected for the Oxisol soil where eggplant was planted.

In many cases the hypothesis of homogeneity of variance was not valid. This is indicated in the tables by NV for the probability of a greater F value. In order to find out if there were any significant trends, orthogonal comparisons were performed for linear, quadratic and cubic trends. The results of this analysis showed that for the pigeon peas and eggplant, there was a significant trend of increasing yield with increasing amounts of sludge, and for the ratoon sorghum crop the trend was cuadratic, first decreasing and then increasing as sludge levels were increased.

3. <u>Grain and foliar macronutrient content</u>:

Macronutrient content of leaf and grain samples are given in tables 5 through 11. Analysis of variance, LSD's and orthogonal comparisons were also performed on this data. In general for the sorghum neither sludge nor fertilizer had any significant effect on leaf or grain content of these elements (Tables 5, 6, and 7). This is in contrast to a previous experiment on an Ultisol in Puerto Rico where the sludge caused a highly significant increase in both phosphorus and magnesium content (Cavallaro and Villarrubia, 1987). Both of these elements however are fairly high in the soil used in the present experiment (see Table 1). Despite this, both phosphorus and potassium in the leaf tissue and calcium content in the fruit were significantly and negatively correlated to yield (see Table 12). Only sodium showed a significant linear trend of increasing concentration as sludge level increased, but the levels were too low to be of any consequence in terms of grain quality.

Results were almost the same for the pigeon peas which were grown on the same area as the sorghum, except that for this crop there was no effect on sodium concentrations (Tables 8 and 9). There was also a significant effect of the first increment of sludge on the phosphorus content of the grain but the trend was a quadratic one, perhaps due to dilution as the yield increased in this crop with sludge additions. Regression analysis revealed a correlation with yield of only magnesium among the macronutrients.

The data on macronutrients in the eggplant are presented in Tables 10 and 11. As expected for this less fertile soil, some differences were detected. In particular, potassium was increased considerably in the leaf tissue by the fertilizer although the sludge had no effect on this parameter in the leaf tissue and in the fruit there was a linear trend of decreasing potassium with increasing sludge. Overall these tendencies resulted in a significant correlation between yield and leaf potassium concentration. Surprisingly, there was no effect on phosphorus concentrations in contrast to the previous experiment by the authors on an Ultisol, and to the results of McLaughlin and Champion (1987) in which sludge was found to be a good source of phosphorus in a sesquioxic soil. There was an almost significant cubic trend for the foliar data whereby the first increment of sludge appeared to increase phosphorus but the concentration decreased again with further increments. This same tendency was seen for magnesium where the first increment of sludge produced a significant increase in concentration. In addition, there was an increase in sodium content for both leaf and fruit with increasing sludge applications, and this parameter in the fruit was significantly correlated to yield.

4. Foliar and grain metal concentrations:

In general, concentrations of heavy metals were in the normal range for all treatments and all three crops (Keefer et al, 1986; Sommers and Barbarick, 1986; Underwood, 1972) (see Tables 13-19) although the lead and nickel concentrations are on the high end of this range for the untreated as well as the treated soil. The concentrations of nickel, lead, zinc and copper are very similar to the concentrations found in sorghum leaf tissue grown on an acid Ultisol (Cavallaro and Villarrubia, 1987), while the sorghum cadmium, manganese and iron concentrations in the present study are one half to one fifth the values as would be predicted for this neutral soil as compared to the acid soil. There were however some effects of the sludge on concentrations of these elements in the leaves. For the first crop, nickel concentration was significantly increased by the highest level of sludge addition, but for the ratoon crop only cadmium showed a significant positive linear trend and this element was also significantly correlated with yield. On the other hand, sludge appeared to decrease both lead and iron concentrations, and lead and copper concentrations in the grain were negatively correlated to yield.

For the pigeon peas, no effect of sludge was seen on the foliar concentrations of these metals and concentrations were considerably lower than those found for this same crop grown on the acid Ultisol site mentioned above for all of these metals except copper as would be expected for this type of soil. Although the effect was not statistically significant, the tendency does appear to be toward an increase in iron with sludge and this is the one plant parameter that was highly and positively correlated to yield ($P<.001$, see Table 12). As for grain quality, there was a significant effect of sludge on cadmium content which shows a quadratic tendency and is only seen for the highest level of sludge addition. The levels of cadmium for all treatments are similar to or below those reported by Keefer, et al (1986) for the edible portions of several grains and vegetables from uncontaminated soils. Grain cadmium content was also significantly correlated to yield. It should be noted that the cadmium concentration in the sludge and the total amount added was very small suggesting that the effect is an indirect one probably by way of increasing the soluble organics in the soil solution. If this is the case, the risk is probably not very great of accumulating high concentrations of cadmium in the soil. Iron and manganese concentrations showed significant positive linear trends with increasing sludge addition also suggesting the involvement of organic molecules, perhaps related to minor changes in redox potential.

For the Oxisol site, eggplant leaf tissue showed significant effects of sludge on copper, lead, zinc and manganese. In all cases except lead, which showed a cubic trend, the increase was with the first increment and thereafter there was a decrease probably attributable to dilution from the increase in yield. For the eggplant fruit, the only significant effect was on lowering the nickel concentra- tions thus improving the quality of the consumable product by reducing the content of this toxic metal. However, it should be noted that the concentration of these metals is on the high end of the normal range (Sommers and Barbarick, 1986) such that these metals should be of concern if higher rates of sludge or several periodic additions are used.

5. Effect of sludge on soil parameters:

Table 20 gives the values for soil pH shortly after treatment and at harvest for the three sites, as well as the harvest values for Bray extractable phosphorus and ammonium acetate exchangeable bases. For the two Vertisol sites, there was no significant effect either of fertilizer or sludge applications on pH values although pH was significantly correlated to yield (Table 24) for both crops. In both crops the sludge did increase the Bray extractable phosphorus while the fertilizer had no effect overall. The exchangeable potassium also increased linearly and the sodium decreased quadratically for the sorghum site while no effect of sludge was seen for the other elements. This soil being quite fertile, these parameters were not related to yield. For the eggplant on the other hand (Oxisolsite), phosphorus, calcium, magnesium and potassium were all correlated to yield and pH was not significantly correlated to yield. However, pH was significantly increased by the sludge, an effect which in this soil is considered generally and significantly decreased by the fertilizer. This same effect was seen in the previous year's experiment on an acid Ultisol. The phosphorus was increased by the sludge and by the fertilizer, as expected, but the effect was not as dramatic as with the Ultisol site where the soil was extremely deficient in this element (Cavallaro and Villarrubia, 1987). The results of the present study are similar to those of McCoy et al (1986) in which the extractable phosphorus was increased by sludge but this increase was not reflected in plant tissue analysis. Exchangeable magnesium, potassium and calcium were all increased by the sludge applications in this soil whereas for the Ultisol calcium and potassium were unaffected, probably because of the greater aluminum content of the latter (Soil Survey, 1967) which blocked the ability for the soil to retain much additional calcium.

Cations extracted with the Mehlich 3 solution for the samples taken at harvest are shown in Tables 21-23. These values are presented because in most cases they show greater effects and less variability than the ones taken two weeks after application. They also reflect better the interaction between the sludge and the soil since two weeks is a relatively short time for soil reactions with organic and low solubility materials. Of the exchangeable bases, this solution extracted more sodium and showed an effect of sludge on this paramter, but for the others, concentrations were similar and the effects about the same. The two extractants were highly correlated for the Oxisol site but high correlations were only seen for potassium in the Vertisol sites (Table 27). In the latter, less potassium was extracted with the Mehlich solution while the values for the other bases were very similar. Only the magnesium demonstrated an effect of increasing concentration with the sludge additions.

Other metals were affected by sludge, depending on the site. Extractable zinc was consistently increased by the sludge additions except that for the pigeon pea site this was not statistically significant. This is in contrast to the data from the Ultisol site where no significant effect of sludge was seen on extractable zinc. In all cases however, concentrations of this element in the leaf tissue were fairly low (<40ppm), and the effect could therefore be considered a beneficial one both in terms of plant response and grain nutritional quality. Copper also increased with sludge application for both the Oxisol and

Vertisol sorghum site. Given the values for copper concentration in the leaf and grain or fruit tissue, this effect could not beconsidered detrimental. For both zinc and copper, concentrations extractable from the soil were positively correlated to yield for the eggplant. Nickel was also increased by the sludge in the Vertisol but the effect was not great and the levels remained within normal range for soils (Overcash and Pal, 1979). Lead and cadmium values are not given here because the concentrations were just barely detectable indicating that there was less than 1ppm extractable Cd and less than 5ppm extractable lead in all of the soil samples.

Table 26 shows that there is a good correlation between Mehlich extractable manganese, zinc, nickel, and copper and their concentrations in plant tissue for the various crops demonstrating that this extractant can be useful in evaluating plant available metals. For the bases calcium, magnesium, and potassium, it gives values that relate to plant tissue about as well as the ammonium acetate extractant normally used for exchangeable bases, and is better related to plant tissue concentrations for sodium.

6. Fractionation of metals:

Table 28 presents the results of the fractionation of copper, manganese, zinc, nickel, lead, cobalt and cadmium in the two soils. Average values are given for the treatments receiving sludge and those not receiving sludge. Themanganese content was five to ten times greater than the other metals, and was also high compared to values reported by others of manganese in several Ultisols, Inceptisols, Entisols, Alfisols, and Spodosols (Shuman, 1985, Singh, et al 1988). Of the elements fractionated, manganese was the only one for which the sum of the fractions was about the same as the total measured. For the other metals, the fractions determined accounted for only about 15 to 60% of the total. Both soils had similar contents and for both the major part was in the manganese oxide and amorphous iron oxide fractions. These results are similar to those found by Tessier, et al (1979) and Singh, et al (1988) except that they found higher proportions in the crystalline iron oxide fraction than was found in this study. Shuman, (1985) on the other hand found the highest proportion of manganese in the organic matter fractions of several Ultisols. No significant changes occurred in the manganese fractions of the Vertisol site due to sludge additions, but for the Oxisol, the sludge appeared to increase the manganese and iron oxide fractions which is reflected in the increase in total manganese in this soil.

The amorphous iron oxide and manganese oxide fractions were the only ones which showed a negative correlation with plant tissue concentrations in the Vertisol site, but no significant correlations were detected for the Oxisol site for this metal (see Table 29).

For copper and zinc, the fractions studied here only accounted for 15 to 20% of the total measured for these soils and this is in agreement with several other studies where more that half of the total copper and zinc was in the residual fraction (Singh, et al, 1988; Shuman, 1985; McLaren and Crawford, 1973). Unlike McLaren and Crawford (1973) and Hickey and Kittrick (1984), but in agreement with the other studies mentioned, very little copper was associated with the organic matter fraction in these soils. The copper for both soils was mainly associated with the amorphous iron oxide fraction whereas the zinc was more evenly distributed among the three oxide fractions studied. As was seen for the manganese, the sludge had little effect on the copper and zinc fractions in the Vertisol but did tend to increase the copper in the amorphous iron oxide fraction of the Oxisol and increased the zinc in all but the crystalline iron oxide fraction for the Oxisol.

For copper, only the manganese oxide fraction was correlated to plant tissue concentrations, and this is a negative correlation. For zinc, it was that crystalline iron oxide fraction that related best to tissue concentrations in the Vertisol, and the amorphous iron oxide content which related best in the Oxisol.

The nickel in these soils was fairly evenly distributed among the different soil fractions but the major portion was in the residual fraction as was also seen in the study by Hickey and Kittrick (1984). The sludge appeared to increase the organic fraction temporarily in the Oxisol and the exchangeable and crystalline iron oxide fractions in the Vertisol. In the latter soil, the crystalline iron oxide fraction was negatively related to plant tissue content and the exchangeable fraction positively related.

Lead was also fairly evenly distributed among the soil fractions with the least amount associated with the manganese oxides. This fraction was negatively related to tissue concentrations at the Vertisol site, whereas the crystalline iron oxide fraction was positively related to this parameter for the Oxisol. No consistent effects of the sludge were seen on the lead fractions in the Oxisol, but in the Vertisol, the sludge appeared to increase the exchangeable fraction slightly while decreasing the crystalline iron oxide fraction.

Cobalt was only detected in the manganese and iron oxide fractions of these two soils and the sludge increased the amount in the manganese and amorphous iron oxide fractions.

Cadmium contents were very low in both soils and therefore only detectable in the fractions with the lowest dilution factors in the methodology. No effect was seen on the fractions due to the sludge, but the manganese oxide and organic fractions were correlated positively to tissue concentrations in the Vertisol.

Conclusions:

In general, no important negative effects were seen by sludge additions to these two soils either on yield, or fruit, grain and forage quality. Positive effects in terms of increased yield were seen in some cases and the increases in iron concentration in sorghum grain and zinc concentration in pigeon pea are seen as positive effects on quality. The increase in cadmium at the highest sludge level studied (24 Mg ha^{-1}) is probably of little concern since the cadmium levels in both soils and in the sludge were very low. The tendency of increasing nickel content seen only in the leaf tissue of the sorghum may be of some concern if levels of sludge many times greater than those applied in this study are used or in the case of applications over a number of years, and this merits further study. However, it should be noted that for the eggplant fruit tissue, nickel content was actually decreased by the sludge additions in the Oxisol. Positive effects on exchangeable bases, pH, and available phosphorus, copper and zinc were seen for both soils, consistent with the earlier findings on an Ultisol with the same source of sewage sludge.

TABLE 1 THRU 29

Table 1: Characteristics of the Untreated Soils

Soil	pH	Bray-p (mg kg^{-1})	Organic Carbon (%)	Exchangeable Bases Ca	Mg	K	Na
				--------cmol kg^{-1}------			
Coto	4.60	9.5	2.75	1.95	0.64	0.14	0.06
Fraternidad sorghum	6.90	33.6	1.64	35.6	11.3	0.76	0.59
pigeonpea	7.00	22.5	1.65	31.0	11.3	0.74	0.58

Table 2: Total Element Analysis of Water Treatment Sludge

pH	6.70
P (%)	0.96
K (%)	0.13
Na (%)	0.09
Ca (%)	4.26
Mg (%)	0.37
Cd (ppm)	2.33
Cu (ppm)	342.5
Fe (ppm)	1290
Mn (ppm)	155
Ni (ppm)	79.0
Pb (ppm)	149
Zn (ppm)	1086.0
Bray-P (ppm)	156
C (%)	13.2
H_2O (%)	38.5

Table 3: Elements Added with Treatments (kg ha^{-1})

Treatment	1	2	3	4	5
Sludge	0	0	8000	16000	24000
P	0	43	76.7	153.5	230.4
K	0	83	10.3	20.6	30.9
Ca	0	81	340.6	681.2	1021.8
Mg	0	8	29.4	58.8	88.2
Na	0	0	7.4	14.7	22.1
Cu	0	10	2.7	5.5	8.2
Fe	0	9.7	10.3	20.6	30.8
Mn	0	9.7	1.2	2.5	3.7
Zn	0	10	8.6	17.2	25.8
Pb	0	---	1.2	2.4	3.6
Cd	0	---	0.02	0.04	0.06
Ni	0	---	0.63	1.26	1.90

TABLE 4 Yield of Sorghum Fodder, Pigeon Pea (grain) and Eggplant (fruit) as Affected by Sludge Additions

Sludge (Mg ha^{-1}	Sorghum first crop	Sorghum ratoon	Pigeonpea	Eggplant
	kg ha^{-1}			
0	15.85	6.90	0.56	19.25
0 (complete fertilizer)	16.95	6.71	1.21	24.22
8	15.29	6.09	0.86	20.62
16	15.69	6.49	1.12	20.92
24	15.32	7.21	1.37	23.47
$LSD_{(.10)}$	----	0.95	----	4.48
P (F)	NS*	.346	NV**	.306
Trends:				
P (linear)	----	----	.120	.120
P (cuadratic)	----	.064	----	----

* not significant, ** not valid

Table 5: Macronutrient Content of Sorghum Leaf Tissue (First Crop)

Treatment	P	K	Ca	Mg	Na
			%		
1	.48	1.11	.44	.21	.03
2	.47	1.04	.43	.20	.04
3	.67	1.33	.49	.24	.02
4	.60	1.05	.46	.21	.03
5	.67	1.21	.49	.21	.05
$LSD_{(.10)}$	.175	.248	---	---	.019
P(F)	.233	.226	NS	NS	.230
P(Trends):					
linear	.173	---	---	---	.057
quadratic	---	---	---	---	.284
cubic	.282	.047	---	---	---

Table 6: Macronutrient Content of Sorghum Leaf Tissue (Ratoon Crop)

Treatment	P	K	Ca	Mg	Na
			%		
1	.53	.91	.39	.17	.02
2	.48	.83	.36	.15	.03
3	.58	.84	.41	.17	.03
4	.56	.93	.42	.14	.03
5	.58	.84	.38	.14	.03
LSD $_{(.10)}$	.05	---	.038	---	---
P(F)	.024	NS	.107	NS	NS

Table 7: Macronutrient Content of Sorghum Grain

Treatment	P	K	Ca	Mg	Na
			%		
1	.36	.25	.10	.12	.02
2	.41	.26	.10	.11	.01
3	.39	.29	.11	.12	.01
4	.36	.26	.11	.12	.02
5	.36	.25	.11	.12	.02
$LSD_{(.10)}$	---	---	.007	---	.0045
P(F)	NS	NS	.184	NS	.082
P(Trends):					
quadratic	---	---	---	---	.047

Table 8: Macronutrient Content of Pigeonpea Leaf Tissue

Treatment	P	K	Ca	Mg	Na
			%		
1	.30	.39	1.30	.22	.02
2	.30	.40	1.22	.19	.03
3	.31	.40	1.09	.20	.02
4	.28	.39	1.28	.23	.02
5	.29	.40	1.11	.22	.02
$LSD_{(.10)}$	.030	---	.248	---	.004
P(F)	.378	NS	.388	NS	.414

Table 9: Macronutrient Content of Pigeonpea Grain

Treatment	P	K	Ca	Mg	Na
	%				
1	.47	1.26	.24	.13	.05
2	.46	1.31	.23	.13	.07
3	.50	1.31	.27	.14	.07
4	.44	1.28	.24	.13	.06
5	.48	1.17	.24	.13	.06
$LSD_{(.10)}$	.039	---	---	---	---
p(F)	.093	NS	NS	NS	NS
P(Trends):					
quadratic	---	.168	---	---	---
cubic	.008	---	---	---	---

Table 10: Macronutrient Content of Eggplant Leaf Tissue

Treatment	P	K	Ca	Mg	Na
	%				
1	.22	1.77	3.82	.57	.08
2	.21	2.46	4.67	.49	.09
3	.25	1.86	3.52	.57	.11
4	.22	1.68	4.10	.61	.13
5	.22	1.77	4.27	.60	.14
$LSD_{(.10)}$	.036	.392	----	.082	.044
P(F)	.222	.017	NS	.150	.161
P(Trends):					
linear	----	----	----	.339	.031
quadratic	.210	----	----	----	----
cubic	.103	----	----	----	----

Table 11: Macronutrient Content of Eggplant Fruit

Treatment	P	K	Ca	Mg	Na
			%		
1	.32	1.97	.20	.12	.10
2	.27	1.86	.19	.12	.10
3	.28	1.73	.24	.17	.09
4	.26	1.75	.20	.12	.10
5	.28	1.63	.19	.11	.11
$LSD_{(.10)}$	----	.215	.044	.027	.018
P(F)	NS	.147	.377	.018	.277
P(Trends):					
linear	----	.029	----	.123	.068
quadratic	----	----	.227	.027	----
cubic	----	----	.253	.014	.238

Table 12: Plant Parameters Correlated to Yield

Crop	Plant Parameter	Correlation Coefficient	Probability
Pigeonp			
leaf	Mg	.483	.031
	Fe	.684	<.0005
grain	Cd	.401	.079
Eggplant			
leaf	K	.381	.097
fruit	Na	.485	.030
Sorghum			
leaf	P	-.399	.081
	K	-.383	.095
	Cd	.443	.050
grain	Ca	-.422	.063
	Cu	-.410	.072
	Pb	-.461	.041

Table 13: Heavy Metal Content of Sorghum Leaf Tissue (First Crop)

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
	mg kg^{-1}						
1	.19	20.01	4.13	2.06	34.16	47.33	171.88
2	.20	19.76	3.50	3.00	33.10	51.83	183.75
3	.15	20.26	3.63	2.13	44.53	48.36	270.63
4	.20	22.26	4.94	2.31	35.28	40.52	177.50
5	.20	24.27	5.38	2.63	35.36	39.90	228.13
$LSD_{(.10)}$	----	-----	.928	----	-----	------	------
P(F)	NS	NS	.022	NS	NS	NS	NS
P(Trends):							
linear	---	----	.035	.343	----	.232	-----

Table 14: Heavy Metal Content of Sorgum Leaf Tissue (Ratoon Crop)

Treatment	CD	CU	Ni	Pb	Zn	Mn	Fe
				$mg\ kg^{-1}$			
1	.11	23.52	4.00	1.13	20.27	11.63	240.63
2	.14	22.27	4.00	.44	17.99	9.78	208.75
3	.15	26.27	4.25	1.25	21.69	11.43	176.25
4	.16	15.26	4.19	.69	19.04	10.81	151.88
5	.18	27.28	3.50	.31	23.80	13.49	130.63
$LSD_{(.10)}$	---	11.03	----	.794	5.61	-----	72.15
P(F)	NV	.390	NS	.205	.430	NS	.064
P(Trends):							
linear	.07	---	---	.052	---	.286	.015
quadratic	---	.314	.283	---	---	---	---
cubic	---	.084	---	---	.274	---	---

Table 15: Heavy Metal Content of Sorghum Grain:

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
				$mg\ kg^{-1}$			
1	.08	50.54	3.13	0	23.01	14.53	37.50
2	.10	47.29	2.94	.69	21.33	13.90	41.88
3	.11	48.04	2.56	0	20.36	14.73	40.00
4	.12	49.04	3.00	.94	21.16	11.84	61.88
5	.08	50.29	3.50	1.38	20.43	13.70	49.38
$LSD_{(.10)}$	---	----	----	1.35	----	-----	20.18
P(F)	NS	NS	NS	.341	NS	NS	.261
P(Trends):							
linear	-----	-----	-----	-----	-----	-----	.135
cubic	----	-----	-----	-----	-----	-----	.160

Table 16: Heavy Metal Content of Pigeonpea Leaf Tissue

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
				$mg\ kg^{-1}$			
1	.18	34.80	6.44	3.50	41.88	35.98	315.63
2	.27	37.03	7.44	3.88	44.52	36.81	318.75
3	.29	32.78	7.75	4.16	45.31	36.19	310.00
4	.23	32.52	8.13	3.88	41.96	36.39	332.50
5	.17	34.78	7.63	4.44	43.99	34.49	372.50
$LSD_{(.10)}$	---	---	1.42	---	---	---	----
P(F)	NS	NS	.348	NS	NS	Ns	NS
P(Trends):							
linear	---	---	.146	.293	---	---	----
quadratic	---	---	.135	---	---	---	----

Table 17: Heavy Metal Content of Pigeonpea Grain

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
				mg kg^{-1}			
1	.06	50.30	8.25	4.50	35.27	9.99	140.00
2	.10	50.80	8.19	6.50	44.52	12.46	131.88
3	.06	34.28	7.19	7.44	42.58	12.53	138.75
4	.09	33.78	9.94	5.06	39.32	13.29	180.00
5	.21	29.78	9.44	6.31	46.37	12.87	179.38
$LSD_{(.10)}$	.070	21.13	---	---	7.34	2.39	45.12
P(F)	.010	.290	NS	NS	.116	.180	.199
P(Trends):							
linear	.120	.184	.278	---	---	.045	.083
cuadratic	.012	---	---	.296	---	.145	---

Table 18: Heavy Metal Content of Eggplant Leaf Tissue

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
				$mg\ kg^{-1}$			
1	.51	24.27	11.81	9.06	27.24	301.80	475.00
2	.52	24.52	11.31	7.81	31.83	396.33	531.25
3	.41	32.03	12.69	11.63	39.40	379.92	643.75
4	.48	24.77	12.50	9.50	26.09	370.86	587.50
5	.46	23,02	13.75	12.13	27.07	319.93	543.75
$LSD_{(.10)}$	---	6.72	2.24	2.97	8.90	82.15	----
P(F)	NS	.192	.356	.109	.097	.249	NS
P(trends):							
linear	---	---	---	.207	---	---	----
quadratic	---	.100	---	---	.140	.07	----
cubic	---	---	---	.098	---	---	----

Table 19: Heavy Metal Content of Eggplant Fruit

Treatment	Cd	Cu	Ni	Pb	Zn	Mn	Fe
				$mg\ kg^{-1}$			
1	.32	24.02	8.00	4.19	25.21	23.19	81.88
2	.29	21.02	5.25	3.00	22.92	27.73	90.00
3	.32	22.52	5.44	4.00	23.27	23.81	66.88
4	.31	29.02	4.75	2.88	27.15	24.63	83.75
5	.36	22.01	5.13	4.06	24.16	21.95	92.50
$LSD_{(.10)}$	---	5.67	1.52	---	---	4.23	---
P(F)	NS	.162	.013	NS	NS	.220	NS
P(Trends):							
linear	---	---	.004	---	---	---	---
quadratic	---	.247	.03	---	---	---	---
cubic	---	.052	---	---	---	---	---

Table 20: Phosphorus, pH, and Exchangeable Bases After Treatments

Treatment	pH1	pH2	Bray-P (mg kg^{-1})	Ca	Mg	K	Na
				--------cmol kg^{-1}--------			
Eggplant:							
1	4.80	4.93	17.45	2.33	0.64	0.07	0.06
2	4.57	4.57	34.88	2.59	0.76	0.11	0.05
3	4.65	4.88	25.94	3.26	0.64	0.07	0.07
4	4.90	4.93	31.39	3.13	0.75	0.08	0.06
5	4.98	5.05	40.61	4.74	0.82	0.08	0.09
$LSD_{.10}$	.24	.10	9.24	1.13	0.17	0.03	--
P (F)	.078	<.001	.005	.003	.408	.078	NS
P(trends) linear	---	---	---	---	.077	---	---
Pigeonpeas:							
1	7.05		43.3	35.6	12.6	0.86	0.58
2	6.95		44.8	36.7	12.4	0.78	0.59
3	6.98		49.2	33.3	12.7	0.79	0.54
4	7.00		47.2	35.6	12.3	0.80	0.60
5	6.92		51.4	33.3	12.6	0.77	0.55
$LSD_{.10}$	--		7.3	3.8	--	--	.048
P (F)	--		.342	.438	--	--	.205

Table 20 (continued):

Sorghum:						
1	6.90	24.3	34.4	12.4	0.58	0.59
2	6.88	26.0	34.4	11.8	0.63	0.59
3	6.90	24.1	34.9	12.3	0.59	0.54
4	6.95	28.3	32.2	11.8	0.67	0.56
5	6.86	32.7	33.3	12.0	0.68	0.57
LSD .10	--	5.38	--	--	0.12	0.04
P (F)	--	.047	--	--	.223	.177
P (trends) linear	--	--	--	--	.032	--
quadratic	--	--	--	--	--	.064

Table 21: Mehlich 3 Extractable Metals in Eggplant Plots

Treatment	K	Ca	Mg	Na	Cu	Mn	Ni	Zn
	----cmol kg^{-1}---------				------mg kg^{-1}----------			
1	0.05	2.31	0.54	0.24	3.15	151	2.37	1.03
2	0.14	2.79	0.62	0.23	3.93	182	2.64	1.87
3	0.06	3.30	0.93	0.23	4.15	151	2.48	1.84
4	0.04	7.76	0.69	0.27	4.07	152	2.45	1.78
5	0.04	6.22	0.62	0.31	5.50	136	2.43	3.91
$LSD_{.10}$	.055	5.46	0.47	0.05	0.83	32	NS	1.18
P (F)	.039	.364	NV	.062	.003	.207	NS	.008
P(trends)								
linear	--	--	--	.014	<.001	.271	--	.001
quadratic	--	--	--	.236	--	--	--	.184

Table 22: Mehlich 3 Extractable Metals in Pigeonpea Plots

Treatment	K	Ca	Mg	Na	Cu	Mn	Ni	Zn
	------cmol kg^{-1}--------				------mg kg^{-1}---------			
1	0.38	38.5	14.7	0.58	13.45	325	4.00	4.25
2	0.31	44.1	13.3	0.59	13.17	375	4.35	3.58
3	0.34	40.2	15.6	0.54	12.97	325	4.03	8.20
4	0.37	42.6	14.4	0.60	13.42	333	4.78	7.64
5	0.37	42.9	21.7	0.55	13.20	342	5.00	8.80
$LSD_{.10}$	.054	NS	5.14	.048	NS	NS	0.92	4.05
P(F)	.249	NS	.076	.205	NS	NS	.267	.268
P(trends)								
linear	--	--	.046	--	--	--	.039	.163
quadratic	--	.271	.139	--	--	--	--	--

Table 23: Mehlich 3 Extractable Metals in Sorghum Plots

Treatment	K	Ca	Mg	Na	Cu	Mn	Ni	Zn
	cmol kg^{-1}				mg kg^{-1}			
1	0.34	40.2	11.8	0.59	13.4	292	3.57	3.25
2	0.42	39.5	14.8	0.59	13.2	341	4.08	3.89
3	0.37	39.8	12.0	0.54	14.2	267	4.50	7.00
4	0.42	40.9	16.6	0.56	13.7	333	4.35	8.13
5	0.36	53.9	15.9	0.57	14.8	292	4.12	8.12
$LSD_{.10}$	0.05	6.8	8.1	0.04	1.0	67	0.82	2.24
P(F)	.086	NS	NS	.177	.101	.309	.382	.038
P(Trends)								
linear	.290	.092	.082	.277	.064	--	.329	.022
quadratic	.067	--	.042	.064	--	--	.104	.102

Table 24: Soil Parameters Correlated to Yield

Crop	Soil parameter	Correlation coefficient	Probability
Eggplant	Exch. Ca	0.382	.096
	Exch. Mg	0.499	.025
	Exch. K	0.662	.001
	Bray-1P	0.544	.013
	Mehlich Mg	0.441	.051
	Mehlich K	0.632	.002
	Mehlich Zn	0.483	.030
	Mehlich Cu	0.504	.023
	Mehlich Mn	0.423	.062
Pigeonpea	pH	-0.491	.027
Sorghum	pH	-0.584	.006

Table 25: Tissue Concentrations Correlated to pH

Crop	Element in Tissue	Correlation coefficient	Probability
Eggplant leaf	Zn	-0.418	.066
	K	-0.655	.001
	Mg	0.386	.092
	Na	0.463	.039
	Mn	-0.377	.101
	Ni	0.581	.007
fruit	Mn	-0.529	.016
	Cd	0.404	.076
	Cu	0.593	.005
	Zn	0.591	.006
Pigeonpea leaf	Cu	0.425	.061
	Fe	-0.392	.087
	Pb	-0.411	.072
	Zn	-0.525	.017
grain	Cd	0.372	.106
Sorghum leaf	P	0.458	.042
	K	0.626	.003
	Ca	0.516	.019
	Mg	0.395	.084
	Cu	0.387	.091
	Fe	0.522	.018
	Zn	0.395	.084
	Cd	0.504	.023
grain	P	0.504	.023
	K	0.614	.004
	Ca	0.451	.046
	Mg	0.509	.021
	Cu	0.423	.062
	Fe	0.431	.057
	Zn	0.614	.004
	Pb	0.391	.088

Table 26: Soil Extractable Elements Correlated to Tissue Concentration of the Same Element

Crop	Soil parameter	Plant part	Correlation coefficient	Probability
Eggplant	Exch K	leaf	0.736	<.0005
	Mehlich K	"	0.754	<.0005
	Mehlich Na	"	0.423	.063
	Mehlich Mn	"	0.357	.122
	Exch Mg	fruit	-0.425	.061
	Mehlich Mg	"	-0.615	.003
	Mehlich Mn	"	0.697	<.0005
	Mehlich Ni	"	0.307	.188
	Bray P	"	-0.358	.120
Pigeonpea	Exch Ca	leaf	0.437	.054
	Exch K	"	-0.514	.020
	Mehlich K	"	-0.393	.086
	Mehlich Ca	"	0.342	.139
	Mehlich Na	"	0.358	.121
	Mehlich Ni	"	0.458	.042
	Mehlich Zn	grain	-0.555	.011
	Mehlich Cu	"	0.504	.023
	Bray P	"	-0.346	.134
Sorghum	Mehlich Cu	leaf	0.500	.024
	Mehlich Zn	"	0.394	.085
	Bray P	"	0.758	<.0005
	Exch Ca	grain	0.440	.052
	Mehlich Ca	"	0.540	.013
	Mehlich Mn	"	0.381	.097
	Mehlich Ni	"	-0.524	.017
	Bray P	"	0.381	.097

Table 27: Correlation Between Bases Extracted with Ammonium Acetate and Mehlich 3

Crop	Element	Correlation coefficient	Probability
Eggplant	Ca	0.863	<.0005
	Mg	0.648	.001
	K	0.968	<.0005
Pigeonpea	Ca	0.300	.199
	K	0.587	.006
Sorghum	Mg	0.432	.057
	K	0.510	.021

Table 28: Fractionation of Metals in Treated and Untreated Soils A: Coto Soil

Fraction		Cd	Co	Cu	Mn	Ni	Pb	Zn
		mg kg^{-1}						
Exch[1]	1	0.29	---	0.48	23.6	3.56	6.60	1.44
	1s	0.30	---	0.48	20.8	3.43	6.20	2.36
	2	0.31	---	0.42	21.4	3.56	6.20	1.30
	2s	0.31	---	0.47	7.3	3.36	5.90	1.97
lsd*		--	---	0.08	8.7	0.50	1.03	0.69
Org[2]	1	0.21	---	1.12	10.1	7.93	2.91	1.50
	1s	0.23	---	1.32	9.9	8.67	3.04	1.85
	2	0.23	---	1.25	10.0	8.58	2.89	1.72
	2s	0.22	---	1.12	10.6	8.41	2.94	2.09
lsd		--	---	0.08	4.4	0.72	0.23	0.13
Mnox[3]	1	0.16	20.7	2.40	667	4.90	1.70	11.7
	1s	0.12	7.2	0.73	712	5.20	2.13	8.6
	2	0.10	13.3	0.60	734	4.70	1.90	6.2
	2s	0.10	13.9	0.60	772	4.13	1.67	8.9
lsd		--	5.0	0.79	52	0.75	0.65	2.6
Feoxa[4]	1	---	59	14.0	293	4.25	7.50	8.75
	1s	---	67.5	16.5	298	4.53	7.83	12.30
	2	---	60.0	14.25	325	4.25	7.75	8.75
	2s	---	68.2	15.80	390	4.32	7.0	10.27
lsd		---	8.0	1.44	59	1.50	2.00	1.74
Feoxc[5]	1	---	54.8	2.00	26	5.75	8.0	6.00
	1s	---	55.7	1.67	27	6.83	6.2	6.33
	2	---	56.0	0.50	29.5	7.00	8.0	6.25
	2s	---	45.0	0.50	41.7	7.00	8.0	6.66
lsd		---	7.0	1.01	11.5	1.40	3.8	2.11
Total	1	0.88	143	116	860	81.2	50	155
	1s	1.06	151	108	913	90.4	53	162
	2	1.18	149	124	854	86.2	47	160
	2s	1.00	148	125	895	90.0	50	165

[1]Exchangeable, [2]Organic, [3]Mn oxides, [4]Amorphous Fe oxides, [5]Crystalline Fe oxides; *mean of sd_0+sd_s for each date (sd = standard deviation); 1,1s: first post treatment samples with and without sludge, 2,2s: samples taken at harvest.

Table 28 (continued) B: Fraternidad soil

Fraction		Cd	Co	Cu	Mn	Ni	Pb	Zn
		mg kg^{-1}						
Exch	1	0.088	----	0.48	1.80	2.72	5.72	1.44
	1s	0.078	----	0.45	2.11	2.80	5.81	2.36
	2	0.068	----	0.52	1.10	2.66	5.74	1.30
	2s	0.072	----	0.51	1.08	3.36	6.13	1.97
lsd		--	--	0.05	0.66	0.62	0.10	0.69
Org	1	0.20	----	2.53	3.36	8.20	2.76	1.50
	1s	0.19	----	2.51	3.39	7.80	2.76	1.85
	2	0.20	----	2.38	4.18	8.10	3.15	1.72
	2s	0.19	----	2.51	4.20	8.20	3.50	2.09
lsd		--	--	0.08	1.80	---	----	0.13
Mnox	1	0.068	6.8	0.70	525	3.8	1.60	11.7
	1s	0.095	9.5	0.73	498	5.4	1.60	8.6
	2	0.112	5.4	1.90	399	5.9	1.10	6.2
	2s	0.085	11.8	1.07	527	5.6	1.16	8.9
lsd		--	6.2	0.75	75	--	--	2.6
Feoxa	1	---	63.0	35.0	343	7.25	5.5	8.75
	1s	---	72.7	35.7	310	6.50	5.5	12.3
	2	---	58.1	32.2	320	9.50	5.0	8.75
	2s	---	66.2	30.7	307	10.00	2.5	10.17
lsd		---	8.2	3.3	24.2	2.75	1.6	1.74
Feoxc	1	2.06	62.5	---	12.5	7.0	3.75	6.00
	1s	1.19	47.2	---	32.2	12.7	2.33	6.33
	2	0.925	55.5	---	29.8	8.0	5.50	6.25
	2s	1.00	60.8	---	23.5	9.83	4.17	6.60
lsd		--	6.8	--	11.6	3.2	1.10	2.11
Total	1	0.88	210**	175	905	68.0	37.5**	160**
	1s	1.06		175	864	76.8		
	2	1.18		180	850	75.0		
	2s	1.00		182	897	74.4		

Table 29: Correlations Between Elements in Different Fractions and Their Concentrations in Plant Tissue

Element	Fraction	Tissue	Correletion Coefficient	Probability
Cu	Mn Oxide	pigeonpea		
		leaf	-0.880	.083
		grain	-0.860	.099
Mn	Amorphous	pigeonpea		
	Fe oxide	grain	-0.815	.118
	Mn oxide	sorghum		
		leaf	-0.960	.023
Zn	Crystalline	pigeonpea		
	Fe Oxide	leaf	0.935	.031
Cd	Organic	pigeonpea		
	Matter	grain	0.840	.102
	Mn Oxide	grain	0.890	.081
Ni	Exchangeable	pigeonpea		
		leaf	0.875	.089
	Crystalline	sorghum		
	Fe oxide	grain	-0.900	.079
Pb	Mn Oxide	pigeonpea		
		leaf	-0.860	.099
	Crystalline			
	Fe Oxide	eggplant		
		fruit	0.830	.109

Literature Cited:

Bingham, F.T.A., A.L. Page, G.A. Mitchel, and J.E. Strong, 1979. Affect of liming an acid soil amended with sewage sludge enriched with cadmium, cobalt, nickel and zinc on yield and cadmium content of wheat grain. J. Environ. Qual. 8:202-207.

Cavallaro, N. and M.B. McBride, 1980. Activities of Cu(II) and Cd(II) in soil solutions as affected by pH. Soil Sci. Soc. Am. J. 44:729-732.

Cavallaro, N. and M.B. McBride, 1984. Zinc and copper sorptionand fixation by an acid soil clay: Effect of selective dissolutions. Soil Sci. Soc. Am. J. 48:1050-1054.

Cavallaro, N. and J. Villarrubia, 1987. Use of sewage sludge as soil amendment: Effect on yield of forage and soil chemical properties. Final Report to the Water Resources Research Program, Department of the Interior.

Council for Agricultural Science and Technology (CAST), 1980. Effects of sewage sludge on cadmium and zinc content of crops. Rep. 83. CAST, Ames, IA.

Greweling, T., 1976. Chemical analysis of plant tissue. Search Agriculture, Agronomy 6. Cornell University, Ithaca, N.Y.

Heil, D.M. and K.A. Barbarick, 1989. Water treatment sludge influence on growth of sorghum-sudan grass. J. Environ. Qual. 18:292-299.

Hickey, M.G. and J.A. Kitttrick, 1984. Chemical partitioning of cadmium, copper, nickel and zinc in soils and sediments containing high levels of heavy metals. J. Environ. Qual. 13:372-377.

Higgins, A.J., 1984. Land application of sewage sludge with regard to cropping systems and pollution potential. J. Environ. Qual. 13:441-448.

Iwai, I., T. Hara, and Y. Sonada, 1975. Factors affecting cadmium uptake by the corn plant. Soil Sci. and Plant Nutr. 21:37-46.

Keefer, R.F., R.N. Singh and D.J. Horvath, 1986. Chemical composition of vegetables grown on an agricultural soil amended with sewage sludge. J. Environ. Qual. 15:146-151.

Maclean, A.J., 1976. Cadmium in different plant species and its availability in soils as influenced by organic matter and additions of lime, P, Cd, and Zn. Can J. Soil Sci. 56:129-138.

McCoy, J.L., L.J. Sikora, and R.R. Weil, 1986. Plant availability of phosphorus in sewage sludge compost. J. Environ. Qual. 15:403-409.

McLaren, R.G. and D.V. Crawford, 1973. Studies on soil copper: 1. The fractionation of copper in soils. J. Soil Sci. 24:172-181.

McLaughlin, M.J. and L. Champion, 1987. Sewage sludge as a phosphorus amendment for sesquioxic soils. Soil Sci. 143:113-117.

Mellbye, D.F., 1982. Sweet corn growth on incinerated sewage sludge amended soil. J. Environ. Qual. 11:160-163.

Mitchel, G.A., F.T. Bingham and A.L. Page, 1978. Yield and metal composition of lettuce and wheat grown on soils amended with sewage sludge enriched with cadmium, copper, nickel and zinc. J. Environ. Qual. 7:165-171.

Overcash, M.R. and D. Pal, 1979. Design of land treatment systems for industrial wastes. Ann Arbor Science, Ann Arbor, MI.

Shuman, L.M., 1985. Fractionation method for soil microelements. Soil Sci. 140:11-22.

Singh, J.P., S.P.S. Karwasra and M. Singh, 1988. Distribution and forms of copper, iron, manganese and zinc in calcareous soils of India. Soil Sci. 146:359-366.

Sommers, L.E. and K.A. Barbarick, 1986. Constraints to land application of sewage sludge. p. 193-126. In E.C.A. Runge et al (ed.), Utilization, treatment and disposal of waste on land. Soil Science Society of America, Madison, WI.

Sommers, L.E. and A.L. Sutton, 1980. Use of waste materials as sources of phosphorus. In R.C. Dinauer and M. Stelly (eds.), The role of phosphorus in agriculture. American Society of Agronomy, Madison, WI.

Tessier, A., P.G.C. Campbell and M. Bission, 1979. Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 51:844-851.

Underwood, E.J., 1972. Trace elements in human and animal nutrition. Academic Press, New York.