Plant-soil interactions of sludge-borne heavy metals and the effect on maize (*Zea mays* L.) seedling growth

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Abstract

The use of sewage sludge as an organic fertiliser under South African conditions is an alternative disposal route to sacrificial land disposal. However, the lack of research done under South African conditions and the conservative nature of the heavy metal guidelines, when interpreted as total metal content is limiting the agricultural use of sludge. A glasshouse experiment, which forms part of a greater project, was conducted to characterise soil-plant interactions of the main sludge-borne heavy metals (Pb, Cd, Zn and Cu) in two sludges (low metal and high metal) to different soil types (clayey, loamy and sandy) on maize seedlings. Growth differences, heavy metal accumulation in plant parts and soil-metal concentrations (total and potentially available) were determined. The low metal sludge treatment showed the highest yield for maize seedlings when compared to controls (soil unamended and inorganic fertiliser added). The amendment of sludge to the soil did indicate higher heavy metal content, although the increase was not as predicted, owing to the difficulty of obtaining a representative sample in the soil. Except for Cd, heavy metal values in the soils (at the beginning and end of experiment) exceeded guidelines due to very high background values in the soil. No negative effects of heavy metal contamination in plant parts of the crops could be proven. Results showed that application of sludge to different soils could be useful in order to increase crop growth over a 28 d period in the glasshouse. Soil, plant and water quality monitoring, together with the prevention of metals entering the plant, is a prerequisite in order to prevent potential health hazards of sludge application to agricultural land.

Introduction

The application of sewage sludge to agricultural land as an alternative to sacrificial land disposal is not a new concept and has been practised throughout the world for the last few decades. The long-term benefits of the application of sewage sludge to land are, however, frequently limited by potentially harmful elements such as heavy metals and human pathogens. Toxic heavy metals, in particular Cd, Cu, Zn, Ni and Pb are frequently present in high concentrations in sewage sludge (Schmidt, 1997). Heavy metals may be transmitted in the food chain and, because of their high toxicity, present a threat to crop production and animal and human health (Korentejar, 1991). However, through previous research done, it appeared that adding sludge to the soil promotes plant growth significantly more than when commercial fertiliser is added. Christodoulakis and Margaris (1996) showed that plant height increased in maize individuals by 77% in the sludge amended treatment compared to 25% in the case of the commercial fertiliser amendment. Previous research done by Snyman et al. (1998) and Henning et al. (1999) has also demonstrated the short-term beneficial agricultural utilisation of sewage sludge concerning heavy metal contamination risk and the cultivation of maize under South African conditions.

According to the 1997 guidelines (WRC, 1997), the current standards for the unrestricted use of sludge on agricultural soils, cannot be attained within a reasonable framework of affordability and applied technology. Snyman et al. (1999) concluded that none of the wastewater treatment works in S.A. could comply with the Cu, Pb and Zn levels in sludge which is intended for unrestrictive use in terms of the total metal content. Investigations that illustrate the benefits of sewage sludge are extremely important, since there is still a general reluctance among agriculturists to recognise the economic value of the sewage sludge in order to improve the soil organic status without contaminating the environment (Korentejar, 1991). As part of a greater research programme, this study was proposed to assess the effect of sewage sludge on growth and yield of maize (*Zea mays* L.) seedlings under glasshouse conditions. Heavy metal concentrations (total and potentially bioavailable) were monitored in the sludge and soil to characterise plant-soil interactions of the sludge-borne heavy metals on different soil types.

Materials and methods

Collection, treatment and analysis of dewatered sewage sludge

Dewatered sludge samples were collected from two different wastewater treatment plants (WWTP) at the East Rand Water Care Company (ERWAT) representing a low metal sludge (Sludge 1) and a high metal sludge (Sludge 2). The low metal sludge (50:50 anaerobic digested sludge and thickened waste-activated domestic sludge) was collected over a period of 4 h from the beltpress facility, while the high metal sludge (anaerobic digested domestic and industrial sludge) was collected from the drying beds after the sludge was left to dry for two weeks. Analyses were done for

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moisture, potentially bioavailable heavy metals (Amm. EDTA method) and total heavy metal concentration (EPA3050 method) of 4 heavy metals (Pb, Cd, Cu and Zn) [Institute for Soil, Climate and Water (ISCW), Agricultural Research Council (ARC), Pretoria].

The NH_4-EDTA method uses 0.02mol dm^{-3} NH_4-EDTA which is sufficient for effective extraction of certain microelements like Cu and Zn, and the solution pH is between 4.5 and 4.8 (The Non-Affiliated Soil Analysis Work Committee, 1990). This method seems to be very efficient in determining microelement bioavailability from soils and is recommended by Bruemmer and Van der Merwe (1989) as the method to be used in predicting the danger of pollution of heavy metals in soils. The EPA 3050 method is a total digestion of metals and does not predict bioavailability. It is an acid digestion used to digest sediments, sludges, and soil samples. This method has been adopted by the U.S. EPA as a standard method and recovers almost 100% of the metals from samples (Sims et al., 1991).

Experimental layout

The experiment was performed under glasshouse conditions and comprised a random block design with four replications and four treatments as stated in Table 1.

TABLE 1
List of the soil treatments used in the experimental design of the glasshouse study on the effect of sewage sludge on maize seedling growth on three soil types over 28 d

Treatments	Soil amendment
Sludge 1	Low metal domestic sludge amended to soil types at 24 t_{dry} ha^{-1}
Sludge 2	High metal domestic sludge amended to soil types at 24 t_{dry} ha^{-1}
Positive control	Inorganic fertiliser amended to soil types as recommended
Negative control	Soil unamended

Soil analyses

Three different soil types were collected in the broader Gauteng area, South Africa, as identified, profiled and characterised by the Institute for Soil, Climate and Water, Agricultural Research Council (ISCW, ARC), Pretoria: a Bonnheim-clayey soil, Longlands loamy sand and Hutton-red sandy loam.

The soil was dried, sifted through a 5mm sieve and stored in a dry room at room temperature. The sludge types (dried) and inorganic fertiliser were added to the different soil types one week before planting at the appropriate rates stated in Table 1. The treated soil samples (sludge treatments and positive control were each used to fill 80 plastic containers (125 x 125 x 120 mm) which were lined with Whatman No. 1 filter paper in order to cover the drainage holes. An additional 16 containers were filled with untreated soil. Maize (*Zea mays* L., cv. Sensako 2472) seeds were planted, 5 per pot. Soil samples were analysed at two different times during the experiment: at the start of the experiment after sludge application and after 28 d of growth. The soil samples which were analysed at the end of the experiment consisted of soil samples and maize seedling roots. Samples were analysed for heavy metal content (total and bioavailable) of four metals (Pb, Cd, Zn and Cu) (ISCW, ARC).

Plant material analyses

Maize seedlings were allowed to grow for 28 d in the glasshouse before harvesting. The above-ground parts were separated from the roots, which were left in the soil for analyses. The foliage was dried at 60°C to determine its dry mass. Above-ground plant samples were analysed for total heavy metal content after drying (ISCW, ARC). The accumulation of metals in the plant parts when taken up from the soil was determined as the *f* factor, also known as the transfer coefficient (Smith, 1996), using the following formula:

$$f = [M]p / [M]s$$

where:
[M] = metal concentration
p, s subscripts refer to plant and soil respectively.

Yield differences between treatments and soil types were measured, and statistically compared, in terms of the shoot length of seedlings and as wet and dry mass of aboveground parts. ANOVA statistical analysis was used to determine the statistical significance of differences between treatments and soil types over the 28 d period.

Results and discussion

Analysis of dewatered sewage sludge

The dried sludge types, Sludge 1 and Sludge 2, had a solids content of 92.5% and 96.5% respectively. Main heavy metals analysed for, and detected, compared to current heavy metal guidelines are presented in Fig. 1.

Figure 1 shows that for both sludge types heavy metal guidelines were exceeded in all cases, except for Cd which was within the guideline limits. This indicates the conservative natures of the

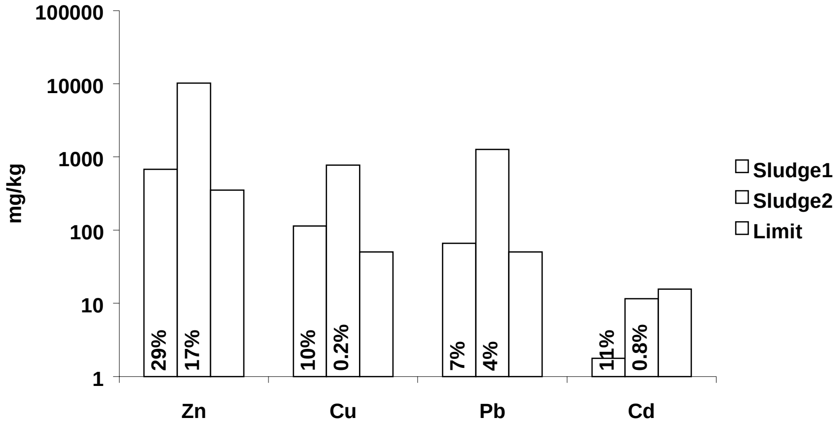
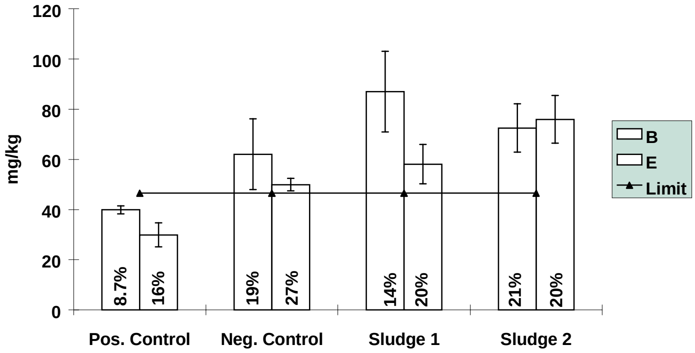
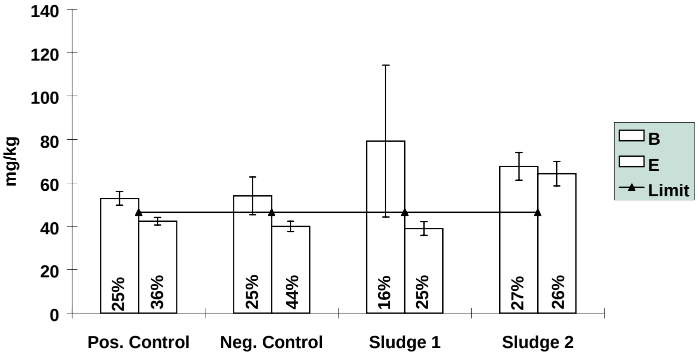
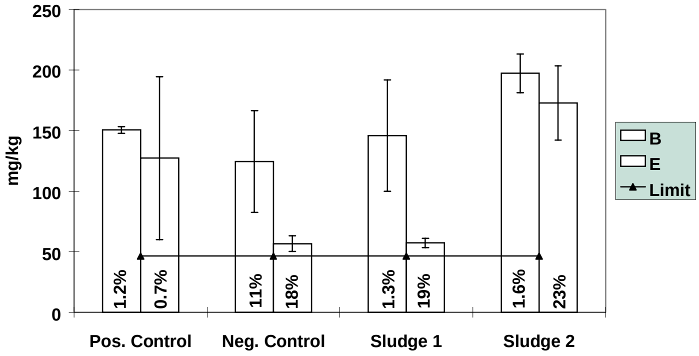


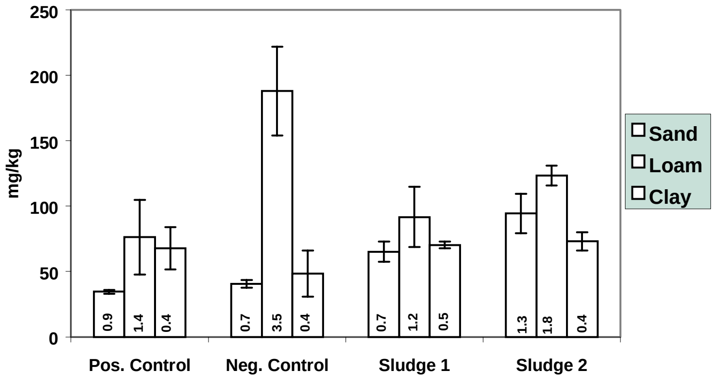
Figure 1
Heavy metal content of two dewatered sewage sludge types compared with the heavy metal guideline limits analysed as total metal content. Percentages within bars indicate percentage potential availability.

South African sludge guidelines when the metal concentrations in sludges are expressed as total metal content (EPA method 3050), and the guideline limits are interpreted as total metal concentrations. Sludge 2 showed high metal concentrations although the availability of the metals was lower than in the case of Sludge 1. This is due to the metals in activated sludges being complexed in different forms, possibly as organic complexes, compared with those present in anaerobically digested sludges (Smith, 1996).









Soil and plant material analyses

Soil pH. Soil pH is one of the major aspects controlling the availability of heavy metals in soils (Smith, 1996). Background pH values of the clayey, loamy and sandy soil types were approximately 8.8, 5.3 and 7.6 respectively.

Zinc. Zinc is a phytotoxic metal, but it is important as a micronutrient at the appropriate levels (Alloway, 1995). As seen in Figs. 2, 3 and 4, Zn concentrations were above the guideline limits in the soil types due to high background concentrations. The availability of Zn in the Sludge 2 treatment did not increase in the sandy and loamy soils, indicating the stability of the metal complexes. The availability of the Zn was more or less the same in the loamy soil compared to the sandy soil. However, the Zn in the clayey soil was far less available at the beginning of the experiment compared to the sandy and loamy soils due to the adsorption of the Zn to the clay particles which increased the cation exchange capacity (CEC) (Alloway, 1995). The increase in the potential availability of the metals in the two sludge treatments in the clayey soil (Fig. 4) was possibly due to mineralisation of the sludge-borne Zn from an organic form (complexed) to an inorganic form (more available for plant uptake). The difficulty in obtaining a representative sample in order to determine the sludge-borne Zn contribution to the soil was evident. In some cases the predicted theoretical increase of the sludge-borne Zn to the soil was different from the analytical contribution measured. For example, the theoretical increase of Zn in the loamy soil should be 6.4%. However, the increase was measured as 32% (Fig. 3).

Figure 5 shows the total Zn concentrations in maize seedling tissue after 28 d of growth. Normal transfer coefficient (f factor) of Zn in maize is between 1 to 2 (Korentejar, 1991). As seen in Fig. 5 the transfer coefficients for Zn in the sandy and clayey soils were lower than normal (except the Sludge 2 treatment in the sandy soil). The lower pH in the loamy soil caused a higher transfer coefficient in the loamy soil and subsequent higher uptake of Zn in the maize seedling tissue.

Figures from top to bottom:

Figure 2
Zinc concentrations in sandy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Zn. [I = Standard deviation (STD)]

Figure 3
Zinc concentrations in loamy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Zn. (I = STD)

Figure 4
Zinc concentrations in clayey soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Zn (I = STD)

Figure 5
Total Zn concentrations in maize seedling tissue in three soil types. f factor indicated within vertical bars. (I = STD)

Zn concentrations reached phytotoxic levels (100 to 400 mg·kg^{1} (Smith, 1996)) in the loamy soil in the negative control and Sludge 2 treatments.

Cadmium. Cadmium is a very mobile and bioavailable metal which may accumulate in crops and humans (Alloway, 1995). Background concentrations of Cd in the sandy, loamy and clayey soils were low and did not exceed guideline limits even after sludge amendment (Figs. 6, 7, 8). There was a significant increase in availability of Cd in the soil types during the experiment, indicating the extent of the mobility of Cd when amended as a sludge-borne metal to soils. Bioavailability of Cd was lower in the clayey soil due to the CEC in clayey soils being much higher, which leads to the formation of stable complexes (Smith, 1996). Cd levels decreased significantly in the soil types over the 28 d due to accumulation of Cd in the plant tissue. The higher extent of increase in availability of Cd in the sludge treatments in the sandy soil, could be due to the mineralisation of Cd from organic complex to an inorganic form for plant uptake. The difficulty in obtaining a representative sample to determine sludge-borne Cd contribution to the soil was evident as previously shown in the sludge-borne Zn contribution. The predicted theoretical increase of the sludge-borne Cd in the sandy soil was different from the analytically contribution measured. The theoretical increase of Cd in the sandy soil would have been 2.6% and 12.5% in the Sludge 1 and Sludge 2 treatments respectively. However, no increase was measured in the sludge treatments. Even lower Cd concentrations were measured in the sludge treatments compared to the negative control (Fig. 6).

Although the bioavailability was lower in the clayey soil, Cd uptake was not lower in seedlings grown in clayey soil (Fig. 9). The plant transfer coefficient (f factor) for Cd was high in all soil types (Fig. 9) since the transfer coefficient for Cd in maize tissue is between 0.01 and 0.05. Soil pH did not play such a major role in the uptake of Cd, since higher uptake was seen in the

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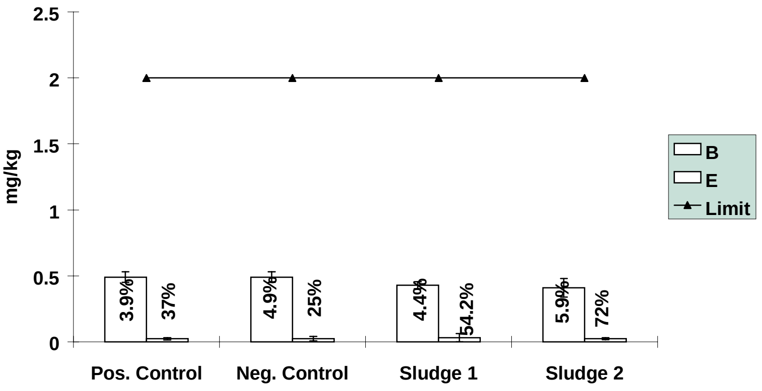


Figure 6
Cadmium concentrations in sandy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Cd. (I = STD)

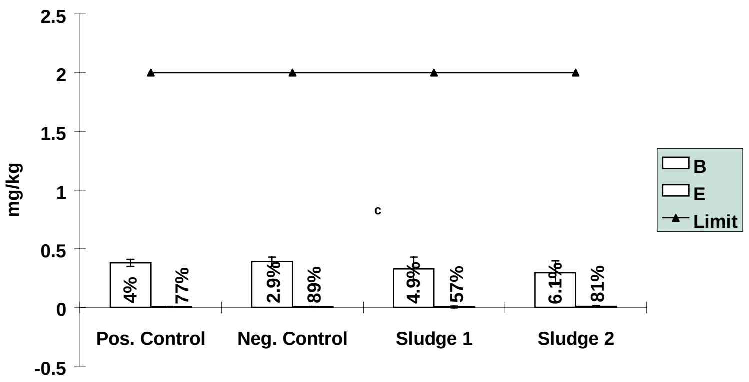


Figure 7
Cadmium concentrations in loamy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Cd (I = STD).

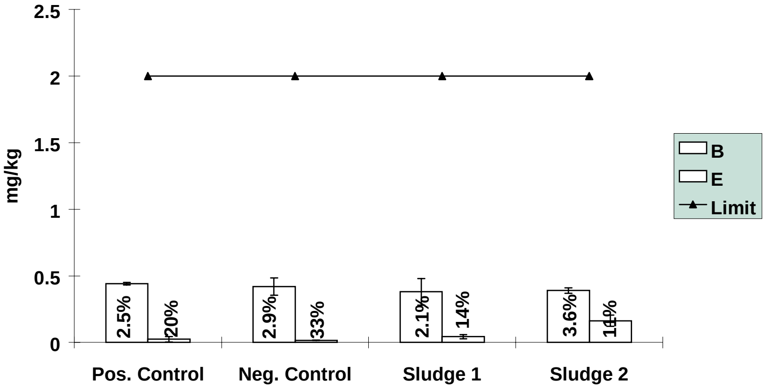


Figure 8
Cadmium concentrations in clayey soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate potential availability of Cd (I = STD).

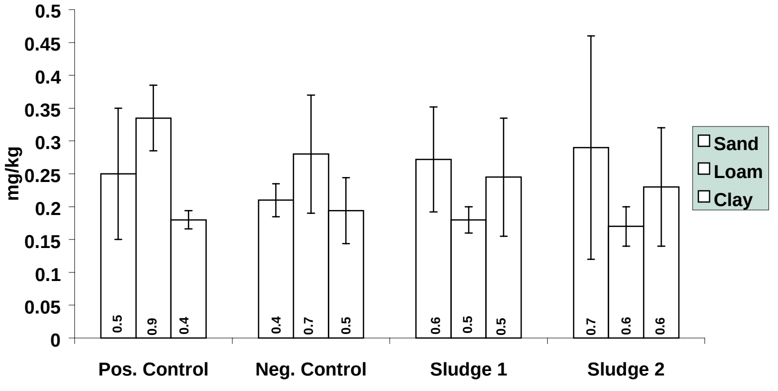
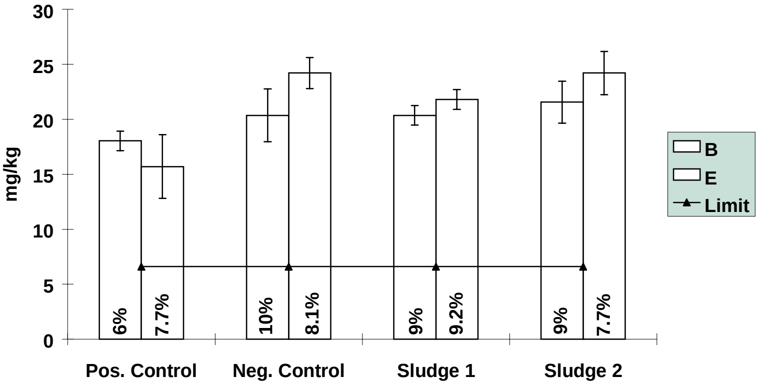


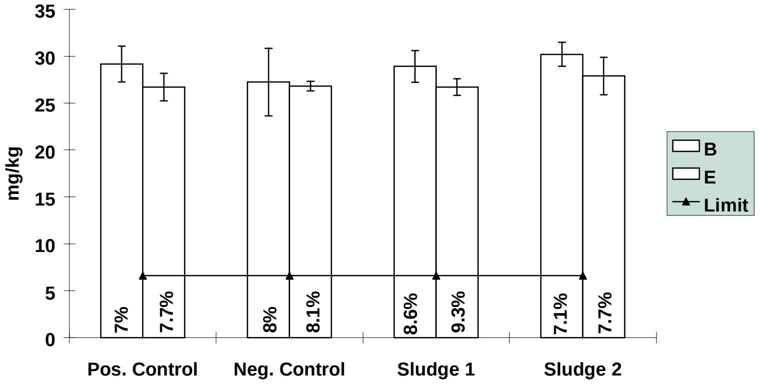
Figure 9
Total Cd concentrations in maize seedling tissue in three soil types. f *factor indicated within vertical bars.* *(I = STD).*

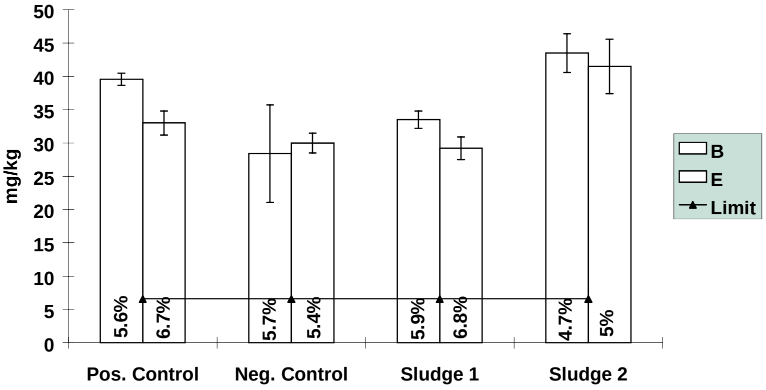
two sludge treatments in both the clayey and sandy soils when compared to the loamy soil, even though calcareous pH causes metal availability to be lower in soils (Alloway, 1995). The uptake of Cd into the maize seedling tissue also did not reach phytotoxic levels of 5 to 30 mg·kg^{-1} even after a single exposure of the sludge types amended to the soil types at a rate of 24 t·ha^{-1} (Smith, 1996).

Copper. Copper is one of the most important essential elements for plants and animals (Alloway, 1995). Figures 10, 11 and 12 show that guideline limits of 6.6 mg·kg^{-1} for Cu were exceeded in the sandy, loamy and clayey soil types due to high soil background levels. Poor sample homogeneity was evident in the sandy soil since the negative control treatment showed higher Cu concentrations than the positive control treatment. Total Cu concentrations and Cu availability remained constant over the 28 d in the soil types, emphasising the fact that Cu is a relatively immobile element (Alloway, 1995). Stable sample homogeneity was evident in the loamy soil, since the predicted theoretical increase of the sludge-borne Cu in the soil was not significantly different from the analytically contribution measured. For example, the theoretical increase of Cu in the loamy soil in the Sludge 1 and Sludge 2 treatments should have been 2.5% and 13.1% respectively. The increase was measured as 5.8% (Sludge1 treatment) and 10% (Fig. 11).

Cu concentrations in seedling tissue did not reach phytotoxic levels of 20 to 100 mg·kg^{-1} (Smith, 1996) as seen in Fig. 13. The normal plant transfer coefficient (*f* factor) values for Cu in maize are between 0.01 and 0.05 (Korentejar, 1991). Therefore, the transfer coefficient for all the soil types was high. Higher transfer coefficient and uptake of Cu in the seedling tissue occurred in the loamy soil, possibly due to the low soil pH which caused a higher availability of Cu in soils for plant uptake (Alloway, 1995).







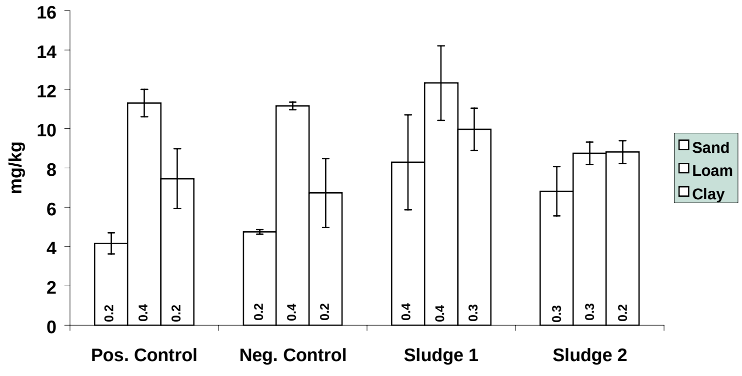


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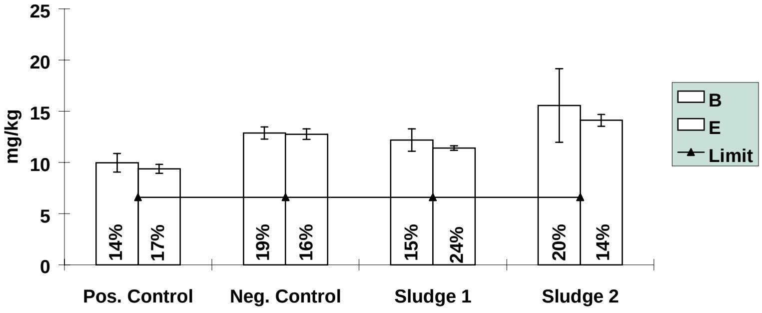
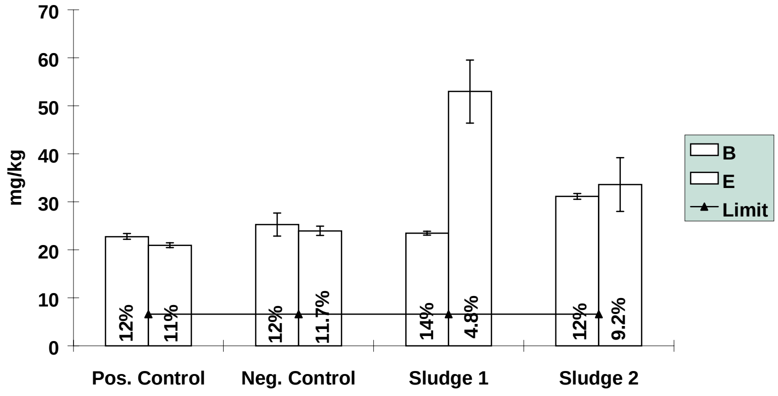
Figure 10
Copper concentrations in sandy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Cu (I = STD).

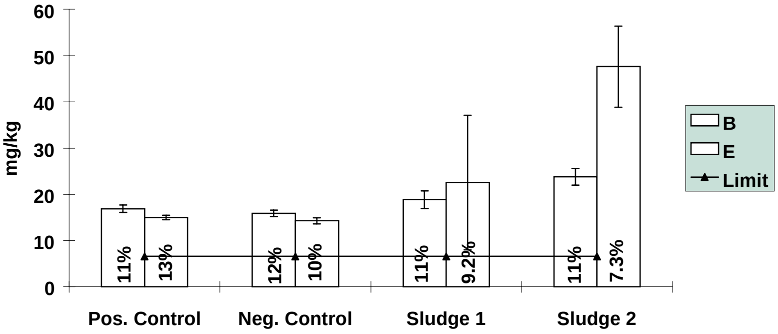
Figure 11
Copper concentrations in loamy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Cu (I = STD).

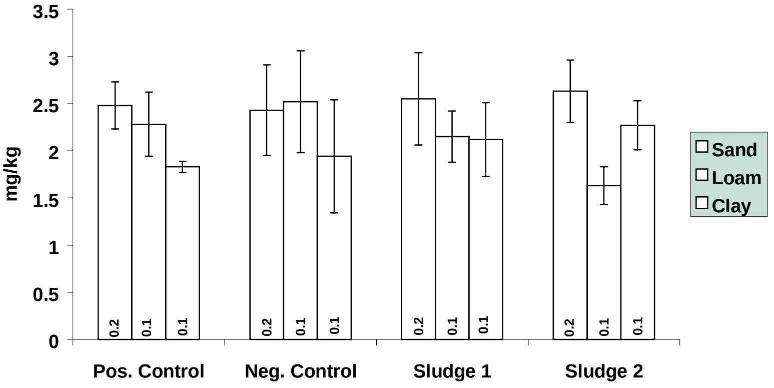
Figure 12
Copper concentrations in clayey soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Cu (I = STD)

Figure 13
Total Cu concentrations in maize seedling tissue in three soil types. f *factor indicated within vertical bars (I = STD)*









Lead. Lead, being a zootoxic metal, needs to be monitored in plant parts used by humans and animals (Alloway, 1995). No significant change could be found for Pb concentrations in the soil types over the 28 d period, indicating the immobility of Pb in soils. Figures 14, 15 and 16 show that the total Pb concentrations in the soil types exceeded guideline limits, mostly due to high background levels in the soils. In both sludge treatments in the clayey soil there was a slight increase in the total Pb concentrations (Fig. 16). The increase in total Pb concentrations in the sludge treatments during the experiments could be due to high root accumulation of Pb. After amendment of the high metal sludge (Sludge 2 treatment) to the sandy soil, the predicted theoretical contribution (44.1%) of the sludge-borne Pb to the total Pb content of the soil was not significantly different from the analytical contribution (36.8%), showing stable sample homogeneity. However, the difficulty in obtaining a representative sample to determine sludge-borne Pb contribution to the soil was also evident. For example, the theoretical increase of Pb in the sandy soil (Sludge 1 treatment) should have been 3.9%. However, the increase was measured as 18.1% (Fig. 14).

Uptake of Pb in seedling tissue was low and did not reach phytotoxic levels of 30 to 300 mg·kg^{-1} (Smith, 1996) as seen in Fig. 17. Normal plant transfer coefficient (*f* factor) values for Pb in maize is between 0.01 and 0.05 (Korentejar, 1991). Therefore, the transfer coefficient for all the soil types was high. Higher transfer coefficient and uptake of Pb in the seedling tissue occurred in the sandy soil, possibly due to the higher availability of Pb for plant uptake over the 28 d in the sandy soil (Alloway, 1995).

Growth

The average shoot length, wet and dry mass per plant are presented in Table 2. There was a definite correlation between wet mass and shoot length of maize seedlings. In the Sludge 1 treatment (all soil

Figures from top to bottom:

Figure 14
Lead concentrations in sandy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Pb (I = STD).

Figure 15
Lead concentrations in loamy soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Pb (I = STD).

Figure 16
Lead concentrations in clayey soil at beginning (B) and end (E) of experiment compared to guidelines (WRC, 1997). Percentages within vertical bars indicate availability of Pb (I = STD).

Figure 17
Total Pb concentrations in maize seedling tissue in three soil types. f *factor indicated within vertical bars (I = STD)*

TABLE 2
Average shoot length (cm), wet and dry mass (g) per plant after 28 d of growth

Parameter	Clayey			Loamy			Sandy		
	Shoot length	Wet mass	Dry mass	Shoot length	Wet mass	Dry mass	Shoot length	Wet mass	Dry mass
Positive control	32.2*^{ax}	2.256^{abx}	0.18^{ax}	36.47^{ay}	2.353^{ax}	0.23^{ax}	33.84^{bxy}	2.078^{ax}	0.19^{ax}
Negative control	31.92^{ax}	1.971^{ax}	0.15^{ax}	32.72^{ax}	2.153^{ax}	0.17^{ax}	30.85^{ax}	1.745^{ax}	0.13^{ax}
Sludge1	48.64^{cx}	4.282^{cx}	0.33^{ax}	46.95^{bx}	3.9^{bx}	0.34^{abx}	51.38^{dx}	4.548^{cx}	0.43^{ax}
Sludge2	38^{bx}	2.908^{bx}	0.16^{ax}	35.73^{ax}	2.572^{ax}	0.35^{by}	38.32^{cx}	2.811^{bx}	0.24^{axy}

*Each value is a mean value per plant of 4 replicates of 20 plants. Values within a row not followed by the same letter (x, y or z), or within a column by the same letter (a, b, c or d) are significantly different (*P*=0.05) according to Duncan's multiple range test.

types), the wet mass and shoot length of the seedlings were significantly higher than the other treatments. A significant increase in shoot length of seedlings grown in the Sludge 2 treatment occurred in the clayey and sandy soils when compared to the two controls. This emphasised the potential short-term beneficial effects of sludges to soils as an organic soil conditioner. This is further emphasised by the fact that no significant difference occurred between the growth of maize seedlings in the different sludge-amended soils. When comparing seedling growth among different soil types no significant differences were seen, although the shoot length of the positive control treatment seedlings grown in the loamy soil showed significant higher values than that of clayey soil.

Soil pH is probably the soil property that affects the uptake of heavy metals the most. It is commonly recommended that soil pH be maintained above 6.5 for sludge-amended soils, although some reports indicated adequate control of metal uptake at pH 6.0 (Sommers et al. 1987). In this experiment the higher uptake of sludge-borne metals in the loamy soil, for example Zn, was due to the lower pH in the loamy soil when compared to the sandy and clayey soils. However, uptake of metals never reached phytotoxic levels in the maize seedling tissue and consequently did not have an effect on plant growth and yield. However, heavy metal behaviour still differs individually and other soil physical properties, like texture, might play an important role in heavy metal behaviour in soils. Today it is commonly accepted that soil type plays an important role in heavy metal bioavailability and, therefore, toxicity (Maclean et al., 1987). This aspect was seen in the soil types used in the experiment, where the metals were often much less available in the clayey soil due to the higher CEC of clayey soils which adsorb metals.

Conclusion

In this glasshouse study, it was found that the current heavy metal guidelines for soil metal concentrations, and sludge metal concentrations, were exceeded in the soil types and sludge types for Pb, Cu and Zn, mostly due to high soil background levels. This emphasises the conservative nature of the current SA guidelines (both soil and sludge metal guidelines) when interpreted as total metal content. Predicted theoretical contribution of the sludge-borne metals, compared to the analytical contribution was different, possibly due to the difficulty of obtaining a representative sample in sludge-amended soils. Long-term experiments still need to be performed on heavy metal accumulation in soil types. However, no phytotoxic effects could be proven, because phytotoxic levels were not exceeded in maize seedling tissue. The sludge affected the yield of the maize seedlings positively compared with control plants. Although the glasshouse experiment showed the beneficial use of sludge on different soil types, the results only represent seedling growth over a 28 d period and cannot conclusively be extrapolated to the field conditions when maize is cultivated at field scale. Therefore a similar large-scale field experiment on maize cultivation will also be completed in the near future, taking into consideration the different environmental parameters. The use of sludge on agricultural soils in SA seriously needs to take into consideration the proper maintenance of soil pH values, for example through application of liming materials. In addition, adequate soil, plant and water quality monitoring procedures are required in order to prevent potential health hazards of sludge application on agricultural land. The possible revision of the SA heavy metal guidelines, when interpreted as total metal content for the unrestrictive use of sludge needs to possibly take into consideration the environmental conditions, crop planted, soil type and sludge type. This might lead to the unrestricted use of sludge on agricultural land in future in SA, causing a decrease in technological costs for wastewater treatment plants (and subsequent financial profit) to eliminate heavy metals in sludges.

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