The production of an artificial soil from sewage sludge and fly-ash and the subsequent evaluation of growth enhancement, heavy metal translocation and leaching potential

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Abstract

The combustion of coal in South Africa produces approximately 22 million tons of fly ash annually. This fly ash has to be handled and stored on ash dumps, which in turn have to be rehabilitated – increasing the cost of ash handling. Sewage sludge is classified as a hazardous, toxic waste. It requires expensive methods of treatment.

This investigation was concerned with the co-utilisation of these otherwise waste products to form an odourless, pasteurised, soil-like product with only the beneficial characteristics of both components (high organic load and low levels of available heavy metals).

The pasteurisation of the sewage sludge is achieved due to the exothermic reaction between the highly alkaline, lime amended, fly ash and the moisture of the sewage sludge. This process is sufficient to treat the sewage sludge to the USEPA PFRP (Process to Further Reduce Pathogens) levels. SLASH has been added to soil to determine whether the bound heavy metals, present in the product from the sewage sludge, are translocated to plants grown in a medium containing SLASH. To date tests conducted on a variety of plants and vegetables have shown no indication of any heavy metal translocation from the soil to the plant. Initial leaching of the SLASH product in simulated rain water has shown leachate levels 2-3 orders of magnitude below the legal limits set for sewage sludge leachate.

Growth enhancement as a result of SLASH addition was analyses in raised bed testing of a variety of plants. All of the SLASH amended soils showed enhanced plant growth.

Introduction

In South Africa approximately 28 million tons of ash are produced annually. This is a largely untapped resource, which is widely used in the cement industry. The benefits of using ash in the cultivation of plants has been extensively investigated (Olbrich, 1995) and research as to its use in the forestry sector is ongoing.

The high heavy metal and toxic element concentration, as well as the pathogenic microbiological load of sewage sludge classify it as a toxic waste and thus requires extensive treatment to ensure a benign product safe for land disposal. Other forms of disposal are also cost-intensive. Future legislation is expected to limit the methods available to the producers for the disposal of the sludge. The organic load in sewage sludge should make it an excellent growth medium but its usage is prohibited by legislation.

It was envisaged that the combination of these two by-products (sewage sludge and fly-ash) could form a pasteurised artificial soil. The advantages of the product would include:

- increased water retention in the soil
- improved physical characteristics of the soil
- decreased erosion potential
- increased biological activity
- substitute for agricultural liming

By combining sewage sludge, class F fly-ash and unslaked lime a soil like product known as SLASH (**S**ewage sludge, **L**ime and fly-**ash**) is produced. A detailed report of the production of SLASH and the establishment of the optimum 6:3:1 ratio has been reported by Reynolds et al., 2000.

To summarise SLASH production, it was suggested that the quicklime (calcium oxide) in the fly-ash would hydrate exothermically with the moisture from the sewage sludge. The resultant increase in temperature and pH would pasteurise the mixture. The conditions require a temperature above 52°C for 12 h and a pH of 12 is required for a week. These conditions would be sufficient to pasteurise the mixture and is so doing eliminating the pathogens from the sewage sludge (Reynolds et al., 2000).

An added advantage of the fly-ash is that any heavy metals in the sewage sludge were expected to be bound in the form of insoluble metal hydroxides in the ash. In this way any translocation of elements would be inhibited. The ash acts both as a bulking agent and a buffer to maintain the pH above 12 in the initial processing. It also plays an important role in odour control as the residual carbon in the product absorbs odorous organics (Burnham et al., 1992).

The product produces carbonates with age and concern was raised about the effect of acid-rain leaching, if the product were to be exposed to the environment for a period of time. Leaching tests, on the product, were conducted according to the South African Department of Water Affairs and Forestry Methodology, for both rainwater and acidic drainage.

The agricultural potential was investigated along with the study on the translocation of heavy metals from the product-amended soil to the plant. A series of pot trials with low SLASH concentrations were undertaken (Reynolds et al., 2000) and based on the results

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obtained follow-up studies were conducted with higher concentrations to determine whether translocation did occur and if so to what extent.

The extent of the benefit of SLASH enhanced soil on plant productivity was also investigated. SLASH can improve the soil texture and fertility, thus resulting in better crop yields. The concept of "Raised Bed Culture" was investigated on flowers and vegetables (Reynolds and Kruger, 1999) and other agricultural crops (Truter et al., 2001).

Methodology

Leaching

The product (SLASH) once produced, may lie in stockpiles awaiting collection. At this point the impact of rain on the potential leachability was considered and this was analysed in a head-over-tail leaching method adapted from the Department of Water Affairs and Forestry.

SLASH was leached by two leachates simulating both landfill leaching (acetic acid) and acid rain leaching. In the case of the acetic acid the toxicity characterisation leaching procedure (TCLP) was used. The leachates were submitted for chemical analysis of the relevant elements.

Plant growth enhancement and heavy metal translocation tests

Following the initial heavy metal translocation tests reported on in WISA 2000 (Reynolds et al., 2000) the following trials were established.

Simple raised beds, each with a surface area of 0.6 m^2 and an effective soil depth of 300 mm, were used in a randomised blocks design with eight treatments and five replications, to evaluate the effect over several cropping cycles. The eight treatments were applied to virgin soil in March 1999. Treatments were SLASH at 0, 2.5, 5, 7.5, 10% of the soil volume, fly-ash at 3% , sewage sludge at 1.5% and lime at 0.5% of the soil volume. Raised beds were watered regularly to eliminate moisture as a limiting factor. Crops in these raised beds did not receive any supplementary inorganic fertilisers, to enhance plant growth.

Plant measurements

These raised beds were initially planted to cut flowers and vegetables in the autumn of 1999 to determine responses (Rethman et al., 1999). The positive results obtained led to a series of grain and cereal crops being planted in these beds over the following summer and winter growing seasons to assess heavy metal translocation, biomass production and the long-term residual effect of the treatments.

Maize was to be the first grain test crop (2nd cropping) to be monitored in the summer of 1999/2000. Once the seeds had germinated, a seedling count was conducted, to determine if there was any effect on the germination of seeds. The beds were initially planted with 20 seeds, which were thinned to ten once the seedling count had been completed. Of these 10 seedlings, plants were harvested when the best treatment reached 200 mm and 400 mm to measure any difference in growth rate at those early stages. The plants harvested were weighed to measure wet mass and the material was then dried at 65°C for 48 h to determine total dry matter production.

Once the remaining plants reached the cob formation stage, the leaves adjacent to the cob were removed and washed with distilled water to remove any dust or particles, which might hinder accurate analysis. These leaves were then analysed for Ni, Cd and B.

When the plants reached full maturity, the cobs were harvested to measure the amount of grain produced and the remaining plant harvested to determine biomass production at maturity. The grain harvested, was also analysed for Ni, Cd and B.

TABLE 1
Results of chemical analysis of the acid rain leachate analysis (µg/g)

Element	Blank	A	B	C	Ave	D	E	F	Ave	G	H	I	Ave	Mean	SLASH product	% leached
As	0.01	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01	**0.01**	**0.01**	<5	0.2
Cu	0.19	159.3	233.5	138.6	**177.1**	149.8	292.8	118	**186.9**	36.4	31.6	32.1	**33.4**	**132.5**	184	72.0
Cd	0.08	0.08	0.08	0.1	**0.10**	0.08	0.11	0.11	**0.1**	0.08	0.08	0.08	**0.08**	**0.09**	0.081	111.0
Pb	0.53	0.6	0.5	0.5	**0.55**	0.53	0.53	0.53	**0.53**	0.53	0.53	0.53	**0.53**	**0.54**	3.9	13.8
Mn	0.08	90.25	101.8	69.0	**86.9**	109.2	271.0	191.1	**190.4**	78.9	86.7	98.1	**87.9**	**121.7**	1156	10.5
Se	0.05	0.05	0.05	0.05	**0.05**	0.05	0.05	0.05	**0.05**	0.05	0.05	0.05	**0.05**	**0.05**	4.0	1.25
Hg	0.005	0.005	0.005	0.005	**0.005**	0.005	0.005	0.005	**0.005**	0.005	0.005	0.005	**0.005**	**0.005**	<0.2	2.5
B	0.13	195.0	198.5	230.5	**208.0**	214.0	219.5	208.0	**213.8**	171.3	183.0	171.0	**175.1**	**198.9**	203	97.9
Mo	0.02	1.30	1.8	2.68	**1.91**	1.41	1.9	1.78	**1.71**	3.9	3.1	3.6	**3.5**	**2.4**	4.35	55.2
Ni	Nd	40.0	53.3	67.8	**53.7**	38.0	39.5	36.3	**89.6**	36.4	31.3	25.9	**31.2**	**58.2**	52.6	110.6
Zn	3.5	16.9	21.9	28.9	**22.6**	14.5	14.4	13.5	**14.1**	12.2	11.9	10.5	**11.5**	**16.1**	210	7.6
Cr	0.25	6.7	7.6	10.2	**8.16**	7.1	6.5	5.4	**6.3**	3.7	3.6	0.13	**2.5**	**5.6**	804	0.7

TABLE 2
Results of chemical analyses of the TCLP (µg/g)

Element	Blank	A	B	C	Ave	D	E	F	Ave	G	H	I	Ave	Mean	SLASH product	% leached
As	0.01	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01	0.01	**0.01**	**<5**	0.2
Cu	0.17	103.8	111.5	117.6	**110.9**	106.5	109.9	104.6	**107.0**	91.8	102.6	108.5	100.9	**106.3**	**184**	57.8
Cd	0.08	-	-	-	**-**	0.08	0.08	0.08	**0.08**	0.08	0.08	0.1	0.09	**0.09**	**0.081**	111.1
Pb	0.53	0.53	0.53	0.53	**0.53**	0.53	0.53	0.53	**0.53**	0.53	0.53	0.53	0.53	**0.53**	**3.9**	13.6
Mn	0.12	863.5	840.0	916.3	**873.3**	737.8	781.8	752.0	**757.2**	851.3	932.8	984.5	922.9	**851.1**	**1156**	73.6
Se	0.05	0.05	0.05	0.05	**0.05**	0.05	0.05	0.05	**0.05**	0.05	0.05	0.05	0.05	**0.05**	**4.0**	1.25
Hg	0.005	0.005	0.005	0.005	**0.005**	0.005	0.005	0.005	**0.005**	0.005	0.005	0.005	0.005	**0.005**	**<0.2**	2.5
B	4.25	202.0	202.8	210.3	**205.0**	227.5	218.0	211.0	**218.8**	200.0	199.5	216.8	216.8	**209.5**	**203**	103
Mo	0.02	3.3	4.3	4.0	**3.87**	7.3	1.4	3.4	**4.0**	2.5	4.3	3.3	3.3	**3.8**	**4.35**	87.3
Ni	Nd	109.7	126.9	127.7	**121.4**	117.5	119.6	107.1	**114.7**	100.2	116.5	123.6	123.6	**116.5**	**52.6**	221.0
Zn	3.5	26.3	36.3	31.8	**31.5**	35.9	36.0	34.9	**35.6**	28.4	28.7		28.6	**31.9**	**210**	15.2
Cr	0.13	6.4	7.2	7.5	**7.0**	6.9	7.2	6.9	**7.0**	5.7	6.7	5.7	6.0	**6.7**	**804**	0.8

Note: Nd = Not detected.
ABC = replicates of each test

TABLE 3
Influence of sludge, lime and ash (both separately and in combination – SLASH) on dry matter production (excluding grain) of maize at different growth stages (relative mass (g))

Treatments		1st harvest (200 mm) (g)	2nd harvest (400 mm) (g)	3rd harvest (mature) (g)
Control	(T1)	0.92	12.3	439.20
2.5% SLASH	(T2)	1.36	14.94	741.80
5% SLASH	(T3)	1.42	16.18	811.60
7.5% SLASH	(T4)	1.62	14.74	878.45
10 % SLASH	(T5)	1.14	14.06	881.75
Sewage sludge	(T6)	15.34	20.00	1049.85
Fly-ash	(T7)	1.26	13.00	533.85
Lime	(T8)	1.02	12.54	492.75

TABLE 4
Maize grain yields of treated soils (relative mass – (g))

Treatment	Grain yield (relative mass (g))
Control	309.45
2.5 % SLASH	713.52
5.0 % SLASH	707.50
7.5 % SLASH	844.37
10.0 % SLASH	1025.98
Sewage sludge	1718.33
Fly-ash	348.10
Lime	451.83

TABLE 5
The mean elemental concentration of leaves of mature maize plants (mg·kg^{-1})

Treatments	Ni (mg·kg^{-1})	Cd (mg·kg^{-1})	B (mg·kg^{-1})
Control	2.908	2.59	27.96
5% SLASH	4.77	3.504	45.71
10% SLASH	3.926	3.192	38.66
3% SLUDGE	3.302	3.318	25.05
Limits set by law*	400	15.7	80

* Kabata-Pendias and Pendias (1984)

Once the maize had been harvested, these beds were planted to *Triticale* (3rd cropping) for the second winter growing season. Biomass production of this crop was measured using three consecutive harvests when plants had reached a height of ± 400 mm. The harvested material was weighed to determine wet mass, and was then dried at 65°C for 48 h to obtain the dry matter (DM) yield of the individual treatments.

Once this crop had completed its growth cycle, these beds where then planted to *Sorghum* spp. (4th cropping) in the second summer growing season. The same measurements were taken for *Sorghum* spp. as for *Triticale*. This multiple cropping was to determine the residual effect of SLASH.

Results and discussion

Leaching

The results of the samples leached in acid rain are shown in Table 1, while those of the TCLP method are shown in Table 2. In both cases a distilled water blank was used for base-line values (blank).

It can be seen that, except for B, Cd and Ni, the elements do not leach to the full potential of the product. This indicates that some of the elements are bound in the product in forms, which are not leachable. The Cd and Ni are, however, probably more susceptible to the acidic leaching (acid rain or TCLP) than to the digestion of the actual product. It thus appears that there is less of the element in the product than in the leachate. Boron is susceptible to leaching in most forms; it was thus expected that B would leach out of the product entirely.

Although the two methods gave similar results it was noticed that Mn, Mo, Ni and Zn leached more in the TCLP leachate than in the acid rain leachate, while Cu leached less. This may be a result of the differing pHs of the leachates.

These results indicate that SLASH does not leach in any extreme manner and emphasises the need for careful soil management if SLASH is to be added to soil for crop growth.

Plant growth enhancement and heavy metal translocation

Maize growth response to various treatments

At 200 mm height, treatment effects could be clearly seen (Table 3). The sewage sludge treatment was by far the best. However, untreated sewage sludge is not recommended for agricultural use, because of it's pathogenicity and heavy metal content. SLASH, fly-ash and lime treatment were not significantly better than the control.

At the 40 cm stage the SLASH treatments were performing slightly better than the control, fly-ash and lime treatments, but not significantly. The differences between these treatments and the sewage sludge was, however, smaller.

Plants harvested at maturity (Table 3) illustrate how the SLASH treatments have benefited plant growth by as much as 200%. The sludge treatment yielded 239% more than the control.

Grain yields (Table 4) indicate similar trends as for the plant material. SLASH treatments gave up to 333 % better yields than the control while the sludge treatment gave 565 % better yields. The risk of heavy metal translocation from sludge will depend on the source of sludge. In contrast, the SLASH product has delivered results which ensure the immobilisation of heavy metals and a safer product to handle and apply in terms of possible disease organisms.

With respect to heavy metals analyses of leaves the results obtained were compared to the limits set by law (Kataba-Pendias and Pendias, 1984) (Table 5).

All heavy metal analyses were below the limits (Kataba-Pendias and Pendias, 1984). These analyses indicate that all treatments had insignificant levels of Ni and Cd, which, were well below toxic levels. SLASH treatments, however, had a higher B concentration, and this can possibly be ascribed to the contribution of B from the fly-ash.

The concern about heavy metal (Ni and Cd) translocation was not supported by the leaf analyses but the concern about possible heavy metal translocation (Ni and Cd) to the grain, which is the most important plant component still prevailed. Analysis of the grain indicated that there had been some translocation but this was evident in all treatments including the control (Table 6). The sludge's Ni and Cd content were similar to that of the SLASH treatments and control. Values were well below limits set by law. The B concentration differed from what was found in the leaf analysis, with considerably less B in the grain than in the leaves.

TABLE 6
The mean elemental concentration of maize grain (mg·kg^{-1})

Treatments	Ni (mg·kg^{-1})	Cd (mg·kg^{-1})	B (mg·kg^{-1})
Control	106.845	9.929	26.605
5% SLASH	102.797	9.361	27.269
10% SLASH	104.450	9.815	29.263
3% SLUDGE	104.135	9.819	25.613
Limits set by law	400	15.7	80

* Kabata- Pendias A and Pendias H (1984)

Triticale growth response

The total plant yields of three harvests of *Triticale* are presented in Table 7.

TABLE 7
Dry matter (DM) g 0.6 m^{-2} production of *Triticale* over 120 d

Treatment		1st harvest (g)	2nd harvest (g)	3rd harvest (g)	Total DM (g)
Control	(T1)	15.84	15.58	28.6	60.00
2.5% SLASH	(T2)	25.06	22.28	35.00	82.34
5% SLASH	(T3)	30.76	27.70	45.16	103.62
7.5% SLASH	(T4)	32.54	31.08	46.46	110.08
10 % SLASH	(T5)	45.76	44.92	53.10	143.78
Sewage Sludge	(T6)	80.72	63.54	76.66	220.92
Fly-ash	(T7)	21.24	21.58	31.00	73.82
Lime	(T8)	19.86	18.08	29.88	67.82

TABLE 8
Dry matter (DM) g 0.6 m^{-2} production of *Sorghum* spp. over 180 d

Treatment		1st harvest (g)	2nd harvest (g)	3rd harvest (g)	Total DM (g)
Control	(T1)	48.72	45.26	46.80	140.78
2.5% SLASH	(T2)	87.24	65.44	60.20	212.88
5% SLASH	(T3)	90.42	69.78	65.72	225.92
7.5% SLASH	(T4)	102.48	82.34	78.18	263.00
10 % SLASH	(T5)	130.40	91.26	92.26	303.92
Sewage Sludge	(T6)	71.24	81.82	89.32	242.28
Fly-ash	(T7)	73.08	56.40	52.56	182.04
Lime	(T8)	47.46	45.64	46.74	139.84

The sewage sludge still delivered a 370 % better DM yield than the control, while the highest SLASH treatment had 240 % better DM yield. The fly-ash contributed only slightly to a better yield but this was not significant. This is understandable because of a low organic matter content and deficiency in essential macro-nutrient content in the fly-ash.

Sorghum growth response

An interesting result was (Table 8) the lower biomass production of the sludge relative to the SLASH treatments with Sorghum in the fourth crop cycle. This could possibly be attributed to an eventual start of depletion of fertility on the sewage sludge treatments. In this fourth cropping cycle, the highest SLASH treatment gave a 215% better yield while the sludge only gave a 170% better yield.

Conclusions

This research confirms that the fly-ash can, if suitably augmented with quicklime, be used to pasteurise a toxic waste like sewage sludge. The resultant product, SLASH, is devoid of pathogens and can be either safely disposed in a landfill or preferably used as a soil ameliorant. The relative amounts of quicklime, sludge and ash used in the formulation are crucial to the achievement of pasteurisation.

The TCLP leaching of the SLASH product showed that the heavy metals of the sewage sludge are immobilised within the fly-ash component and do not leach out in either of the simulated conditions. Although the two methods gave similar results it was noticed that Mn, Mo, Ni and Zn leached more in the TCLP leachate than in the acid rain leachate, while Cu leached less. This may be a result of the differing pHs of the leachates.

In the agricultural trials, with the exception of sewage sludge, SLASH offered greater benefits than any individual ingredients. Sewage sludge, although offering better growth, cannot, however, be recommended due to the pathogenicity of the sludge and heavy metal content and the fact that the heavy metals are not immobilised in the sludge, as they are in the SLASH.

The use of a soil ameliorant based on sewage sludge and fly-ash has definite agricultural potential. The ameliorant has promising liming qualities, improving the pH and maintaining it for a minimum of 18 months as recorded to date. For how long this effect will persist is still to be determined. It is also a promising plant yield enhancer. From the results of these raised bed trials it can be concluded that SLASH has a long-term residual effect, and can be seen as a slow release source of elements required for plant growth.

Although SLASH is seen as good source of nutrients required for plant growth, it does not contain a full range of nutrients. It is devoid of K for example, and the need will exist for supplementary fertilisation.

7.5 % to10% rate of SLASH application ultimately delivers the best results compared to the rest of the SLASH treatments. Under regulated experimental conditions there was no toxic elemental uptake. The two potential-problem heavy metals, Ni and Cd, and the micro-nutrient B, which can be toxic at very high levels, are within the current safety specifications but may be open for review.

For economic reasons the use of SLASH at high levels is limited due to high transport costs, and the recommendation is that this ameliorant's use be restricted to sites in relatively close proximity to the waste raw materials used in its manufacture.

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