A review of the agricultural use of sewage sludge: benefits and potential hazards*

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Abstract

Application of sewage sludge on agricultural land may provide an economical way to dispose of the increasing amounts of sludge generated in the major metropolitan areas of South Africa. The major benefits of sludge application are, *inter alia,* increased supply of major plant nutrients (in particular N and P); provision of some of the essential micronutrients (e.g. Zn, Cu, Mo, and Mn); and improvement in the soil physical properties, i.e. better soil structure, increased soil water capacity, and improved soil water transmission characteristics. The benefits of sludge application may be limited by its potential health hazards, i.e. transmission of pathogenic organisms, accumulation of nitrates in ground water, soil and water contamination by highly toxic organic constituents of the sludge, and accumulation of toxic heavy metals in soil, water and crops. Of these factors, the greatest potential health hazard appears to be the danger of the transmission of heavy metals and pathogenic organisms from the sludgeamended soil to crops, grazing animals and humans. These problems can be minimised by measures such as maintaining the soil pH above 6,5 (by liming), the use of appropriate sludge application techniques, and frequent monitoring of the soil, plant and water quality at the site of application.

Introduction

The growing problem of the disposal of excessive amounts of sewage sludge, generated in the countries of the European Community and the USA, has stimulated research into the use of sewage sludge in agriculture (Champion, 1985). Sludge is used by farmers and market gardeners as a loc-cost, low-analysis N and P fertiliser, to supplement conventional inorganic fertilisers. Furthermore, since sludge contains large amounts of organic matter, it can also be used as a valuable soil stabiliser, to prevent runoff and erosion (Hensler *et al.,* 1970). In the RSA sewage sludge is used by the vegetable farmers in the Philippi Cape Flats area (Palmer, 1989), and in Natal for forage grass and sugar cane production (Easton, 1983; Water Research Commission, 1985a). Recent advances in sludge digestion and sludge pasteurisation techniques (Trim and McGlashan, 1985; Water Research Commission, 1985a b, 1989) to minimise the hazards of pathogenic organisms (present in the sludge), should result in increased usage of the sludge in agriculture.

In South Africa, over 55% of sludge is disposed of in landfills, lagoons and other dedicated land sites located near major urban areas, i.e. centres of industrial activity (calculated from the data in Smith and Vasiloudis, 1989). However, many of those sites are nearing the end of their life span, and the pressure on municipalities for environmentally sound disposal practice is increasing. Furthermore, because of the rapid population growth and increasing industrialisation, municipalities and industries in the RSA are generating increasing amounts of sludge. For example, int he Cape Peninsula area, a future annual growth rate of 6,6 % in sewage sludge production has been projected (Palmer, 1989). To accommodate this increase, sludge disposal on wheat farm land is presently being recommended (Palmer, 1989). The main motivation for the utilisation of sludge in agriculture is the fact that it appears to be the cheapest option for safe disposal (Palmer, 1989). Uncontrolled disposal of sludge, may however, result in the contamination of land and water resources to such an extent that they are unsuitable for agricultural production. Hence, in evaluating the potential for increased sludge use in agriculture, careful consideration of the benefits of the sludge application and its potential health hazards is needed.

In this paper the pros and the cons of sludge utilisation in agriculture, with a particular reference to soil and climatic conditions in the RSA, are discussed.

Agricultural value of sewage sludge

Studies have shown that the yield of many plant species, i.g. field crops, forages, ornamentals and, to a lesser extent, vegetables and conifers, increases following the application of sewage sludge. This can be atrributed mostly to the increased supply of the nutrients as a result of sludge application. Sludge can be considered as a low-grade fertiliser, roughly equivalent to a 4-2,5-1 commercial mixture. The composition of sludge is extremely variable, but it generally contains all the major and minor plant nutrients, except for potassium (Table 1). However, in comparison with commonly used inorganic fertilisers, the concentration of plant nutrients in sludge is rather low, e.g. median values of 28,9 and 13,5 $g.kg^{-1}$ (dry weight) for the N and P content of the sludge (Table 1) as compared to 260 and 110 ($g.kg^{-1}$) for the N and P content of the common inorganic fertilisers (limestone-ammonium nitrate and superphosphate, respectively). Associated with the low elemental concentration is the high cost of transportation of the sludge (per unit weight of the element) as compared with inorganic fertilisers. This is particularly important in a large country like South Africa where major cities are relatively far from main agricultural production areas. Because of this economic factor, it is unlikely that sewage sludge will ever become a major portion of the fertiliser in South Africa. It may, however, be beneficially used as a supplementary fertiliser source in areas located near major sewage treatment plants.

Sewage sludge may be treated by several processes, but even a single process can produce a highly variable product depending on factors such as the season of the year and the influent composition. However, a specific digestion process tends to produce material with a fairly constant C:N:P ratio. Furthermore, the median and the mean values for the N and P levels in various sludges tend to be similar, indicating that the concentrations of the major nutrients are generally within a narrow range (Table 1). In most cases sewage sludge could, accordingly, be viewed as a low-cost,

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TABLE 1
NUTRIENT CONTENT OF SEWAGE SLUDGE IN SOUTH AFRICA

Province	N	P	K (g.kg⁻¹)	Ca
Free State				
Range	17,3 - 41,7	5,8 - 14,8	1,20 - 2,40	20,0 - 59,2
Mean	24,5	9,88	1,82	35,7
Median	21,4	9,30	2,00	34,3
Transvaal				
Range	15,7 - 58,4	7,40 - 41,0	0,80 - 10,5	49,7 - 16,5
Mean	34,5	20,1	3,17	31,7
Median	33,9	17,0	2,30	30,2
Natal				
Range	17,8 - 35,4	10,8 - 31,1	1,3 - 10,9	15,0 - 28,5
Mean	28,9	18,9	2,9	21,8
Median	28,9	16,1	1,5	22,1
Cape				
Range	16,8 - 53,4	4,1 - 20,0	0,7 - 5,2	11,4 - 79,3
Mean	29,7	11,2	1,9	33,2
Median	27,6	10,9	1,5	28,6

Source: Smith and Vasiloudis, 1989

low-analysis N-P fertiliser, in accordance with the Fertiliser Act (Government Gazette, 1947) which governs nutrient levels and its acceptable variability in fertiliser materials. In the following section some of the chemical, biological and climatic factors affecting the fertiliser efficiency of sewage sludge are discussed.

Sludge as a nitrogen fertiliser

In most cases the nitrogen content of the sludge determines maximum annual application rates (US EPA, 1983). In principle, sludge is applied to provide plant nitrogen requirements equal to the nitrogen fertiliser recommendation rates. While plant nitrogen needs can be assessed with some certainty, availability of the sludge-derived nitrogen (and phosphorus) is more difficult to predict. Nitrogen in sludge exists predominantly in an organically-bound form. As such, it must be transformed to inorganic forms by the process of mineralisation prior to plant uptake. This means that, in general, the availability of N from sludge is considerably lower than from the commercial inorganic fertilisers, implying that the cost of fertilisation with sludge would be higher (per unit weight of N) than that of the commercial inorganic fertilisers. However, in certain situations the low rate of release of inorganic-N from sludge could be a desirable feature which may increase its availability. For example, when the efficiency of N fertilisation is limited by factors such as high NO_3^- -N leaching losses (e.g. on sandy soils) or high volatilisation losses of NH_4^+ -N (e.g. in high pH soils), the use of sludge as a slow-release N material may decrease the N losses and increase N availability. It appears that sludge could also be used as a maintenance N fertiliser for perennial crops, e.g. sugar cane (Water Research Commission, 1985a), grasses (Easton, 1983), vines, and fruit trees.

The rate of decomposition of organic matter in sludge is highly variable and depends on the type of waste-water treatment process, and factors such as sludge composition, pH and temperature, etc. With respect to the organic-N, a commonly used estimate of the rate of mineralisation for the first year after application is 40% for unstabilised and waste-activated sludge, 30% for aerobically-digested sludge, 20% for anaerobically-digested sludge, and 10% for composted sludge (Sommers *et al.,* 1981). The US EPA suggests a bulk figure of 3% yr^{-1} of the organic-N for all types of sludge at 4 or more years application (US EPA, 1983). In general, attempts to develop predictive models for the rate of mineralisation as affected by the soil and sludge properties for a wide range of soils and wastes have not been very successful (King, 1984; Parker and Sommers, 1983; Harding *et al.,* 1985). Hence, no standard method for the assessment of the fertiliser-N value of the sludge is likely to be developed in the near future.

High volatilisation losses of ammoniacal-N from sludge may also be a factor limiting sludge-N efficiency. The US EPA estimates that the fraction of NH_3 volatilised from sludge varies from 0 % (for the surface-applied sludge) to 50 % (for soil-incorporated liquid sludge) (US EPA, 1983). The actual loss depends on soil, sludge and climatic factors. Beauchamp *et al.* (1978) found that the "half life" of NH_4^+ -N in sludge was from 3,6 to 5,0 d. Donovan and Logan (1983) found that the cumulative volatilisation increased with time and that 32% of the NH_4^+ was lost in the first 24 h before sludge was incorporated. In cases when the main objective of the sludge application is sludge disposal rather than sludge utilisation as a fertiliser-N material, delaying sludge incorporation may offer a way of maximizing NH_4^+ -N volatilisation loss, hence improving land disposal capacity.

Sludge as a P fertiliser

The interest in the utilisation of sewage sludge as P fertiliser can be attributed, in part, to the fact that the P content of sewage sludge has been increasing, due to the increasingly stringent standards placed on effluent treatment works with regard to soluble P concentration (Kirkham, 1982; Furrer and Bollinger, 1981; Sommers, 1980). Furthermore, P is generally considered to be the most expensive of plant nutrients applied to agricultural soils and the amount of P-bearing minerals in the world is limited (White, 1981). Most of the studies on P fertilisation with sewage sludge have been conducted in cool or temperate climates where large areas of P-deficient soils are uncommon (King and Morris, 1972; Kelling *et al.,* 1977; Sikora *et al.,* 1982; Gestring and jarrel, 1982). In contrast, the largest areas of P-deficiency are located in the tropical and subtropical areas, where acid sesquioxidic soils with very low P status and high P fixation capacity are commonly found. Since organic materials are known to block P adsorption sites in sesquioxidic soils (Fox and kamprath, 1970), it is advantageous that the major portion of P present in the sludge is in organic form, rather than a readily available orthophosphate-P ion. Furthermore, sludge could also be used as a valuable liming material for the acid soils of the tropics, due to its high Ca content (Sommers *et al.,* 1976).

In a recent study of P availability from sewage sludge in P-fixing soils from Natal conducted by McLauchlin and Champion (1987), sewage sludge application compared favorably with that of superphosphate. The study indicated that sewage sludge could be used as a potential P source in the highly weathered soils of Natal, particularly for perennial crops such as sugar cane. A factor which may, however, limit the use of sludge as a P fertiliser is the fact that it generally contains too much P and not sufficient N, in comparison with the crops' requirement. Hence, when the rates of sludge application are based on the crop N demand, the P supplied will be in excess of the crop needs. Application of the excessive amounts of P may result in undesirable environmental consequences, i.e. P accumulation in runoff water, and ultimately, in surface water reservoirs. P accumulation of surface water is the major factor contributing to enhanced growth of algae and mycrophytic plants (i.e.

eutrophication process) and a resulting decrease in water quality. This presents a potentially serious threat to the quality of water supplies, as surface water is the major source of drinking water in South Africa. In such situations application rates must be based on the P requirements of the crops, and not on its N requirements.

Sludge as a source of micronutrients

Applying sludge as a source of major elements may simultaneously correct crop micronutrient deficiencies. Sludge typically contains Cu, Mn, Zn, Mo and B (Smith and Vasiloudis, 1989), which are essential plant micronutrients. Supplying micronutrients through sludge is particularly effective for elements such as iron and zinc, because the chelating properties of sludge organic material enhance plant availability. Micronutrient levels in plant tissue often increase when plants are amended with sludge. Application of excessive levels of sludge should, however, be avoided since it may lead to the accumulation of phytotoxic levels of micronutrients in plant tissue, which may impair plant growth and endanger the health of human beings and animals feeding on the crop. This subject is discussed in more detail in the section "Pollution hazards of sewage sludge".

Sludge as a soil ameliorant

Sewage sludge can be utilised as a soil amendment to increase the organic content of soil, in order to improve the physical condition and to increase the water-holding capacity of the soil. A gradual decrease in the organic matter content of cultivated soils in the world, as a result of factors such as excessive use of mineral fertilisers, is a world-wide phenomenon. In the warm areas (like South Africa) this process is accelerated due to rapid microbial decomposition of the soil organic matter. The decrease in soil organic matter content is a problem of major concern since it may lead to a deterioration of the soil physical status and accelerated erosion. The irreplaceable loss of agricultural soil due to soil erosion and the concomitant decrease in crop productivity are considered one of the main environmental problems on the African continent. The addition of sludge could provide a measure to maintain the organic status of the soil and to minimise the danger of runoff and erosion. This is particularly true for sludge compost, which contains relatively small amounts of nitrogen and phosphorus and is therefore primarily useful as a soil conditioner rather than a fertiliser.

The provision of adequate amounts of organic matter is an important requirement for improving the productivity level of very sandy soils with low organic matter content, like the coastal plains area of the Cape Peninsula. In this area the addition of sewage sludge (mixed with animal manure) has been practised for many decades as a means of maintaining adequate water holding capacity of the soils used for intensive vegetable cultivation. In a similar way, sewage sludge can also be used as a soil ameliorant in the reclamation of coal mine dumps, which have a very low organic matter content. In this case, the establishment of grass cover (to stabilise the dump) is frequently dependent on the provision of adequate organic matter to minimise dump erosion.

The effect of sewage sludge addition on the soil physical properties has recently been reviewed by Metzer and Yaron (1987). Bothe the amount and the composition of the sludge organic matter added to the soil affect the extent to which its physical properties are modified. The most significant effects of sludge addition are the increased water retention and improved water stability of the soil aggregates. The improved soil physical status following the addition of sludge frequently results in improved water transmission characteristics (e.g. higher hydraulic conductivity and increased water infiltration rate) as well as reduced amounts of runoff and erosion. It must be emphasised, however, that at relatively low sludge application rates of sludge (e.g. 7 to 25 $t.ha^{-1}$ based on the N requirements of crops, US Department of Agriculture, 1978), the changes in the soil physical properties are not very pronounced. Repeated applications of sludge over a period of many yeas may be required to bring about a significant increase in the soil humus content and the desired improvement in the soil physical status (Metzer and Yaron, 1987).

Pollution hazards of sewage sludge

Municipal sludges contain a large diversity of pathogenic organisms and toxic chemicals which may endanger human and animal health and impair the growth of plants. The principal causes of concern are pathogenic organisms, nitrates, heavy metals and toxic organic chemicals. Due to the ubiquitous presence of a large variety of pathogenic organisms, e.g. bacteria and viruses, sludge should be considered a biologically hazardous material. Nitrate accumulation in ground water following excessive applications of sewage sludge, inorganic-N fertilisers and animal manures is a common phenomenon in the intensively cultivated areas of Western Europe (De Haan, 1987). Toxic heavy metals, in particular Cd, Hg, Pb, Zn, Mo, and Ni are commonly present in sludge. They accumulate in the environment and hence present a serious long-term pollution problem. Similarly, a large variety of toxic organic chemicals present in sludge are xenobiotic and resist microbial degradation. The presence of excessive levels of any of these toxic components may restrict the levels of application of sewage sludge on agricultural land. Problems associated with the danger of biological contamination and the presence of the toxic components in sludge are further discussed.

Pathogens

The most common pathogens present in sewage sludge are bacteria, protozoa, helminths and viruses. The potential problems of biological pollution by sewage sludge are: contamination of surface water and ground water by pathogens transported by runoff and percolation water; adherence of sludge to crops, and direct ingestion of the sludge by grazing animals. The majority of pathogens in sludge are rapidly inactivated in the soil system (Reddy *et al.,* 1981). Some pathogenic protozoa and helminths, may however, survive in soils for months to years (Burge and Marsh, 1978). Surface application of sludge tends to result in a rapid destruction of the pathogens due to a combined effect of elevated temperature, and accelerated drying (Reddy *et al.,* 1981).

In order to minimise the hazard of biological contamination, a waiting period before the last application of sewage sludge and harvest is recommended. The length of the waiting period varies from one month (in the case of areal crops not contacting the soil, e.g. wheat) to six months (in the case of root or low-growing crops) (Sommers and Barbarick, 1986). Other protective measures include limiting public access to disposal sites, adequate buffer zones around the sites, and injection of sludge below the soil surface level. The potential for ground-water contamination by pathogens following sewage sludge application on agricultural land appears to be minimal (Sommers and Barbarick, 1986). In general, strict adherence to the required minimum waiting periods following sludge application and the use of appropriate sludge application methods should minimise the danger of potential pathogen transmission from sewage sludge.

In the RSA, the health hazards associated with the use of sewage sludge on land for crop growth are likely to be greater than in the USA and in the EEC countries. This is because the risk of pathogen infection is much greater due to the endemic presence of parasites (such as round worms) in a large portion of the population, and a warmer climate. Tentative hygienic quality norms for the use of sewage sludge in agriculture in the RSA have been proposed (Oberholster, 1983). Present restrictions regarding the hygienic quality of sewage sludge refer to the maximum permissible number of *Ascaris* ova, *Salmonella* organisms and faecal coli in the sludge (Vivier *et al.*, 1988).

Nitrate accumulation

Application rates of sewage sludges not containing excessive amounts of potentially toxic metals or organic toxins are generally determined by the crop N requirements. If application rates are too high, excess NO_3^- -N accumulates in the soil and hence may reach ground water (Kelling *et al.*, 1977; Higgins, 1984) or may accumulate in the crop. High nitrate levels are toxic and may cause a development of methaemoglobinemia in infants, due to nitrate combining with the foetal hemoglobin. Unlike heavy metals and toxic organics, NO_3^- is not adsorbed on the soil constituents and thus can be leached below the root zone. This is a particularly serious problem in areas of shallow ground water table, where NO_3^- leaching may result in the contamination of the aquifer. For example, in the recent sampling conducted in the Cape Town area where sewage sludge is used for vegetable production, the NO_3^- -N content of ground water was greater than 20 mg.ℓ NO_3^- -N (unpublished results). By way of comparison, the present drinking water standard, as legislated by the Department of National Health and Population Development, is 10 mg.ℓ^{-1} NO_3^- -N. The problem of nitrate contamination of ground water may be particularly serious in rural areas relying on ground water as a source of drinking water. To prevent such undesirable accumulation of excessive amounts of NO_3^- in ground water, a proper estimation of soil-available N and the crop N needs is needed.

The availability of organic-N compounds in sludge varies considerably, depending on factors such as the origin of the sludge and climatic conditions. Furthermore, because of a large rainfall variability and the associated variability in water stress, fertiliser-N requirements in South Africa vary considerably (Korentajer *et al.*, 1989). Hence, overseas norms for sludge-N application rates may not be applicable to the local conditions. Additional research is required to assess the rate of mineralisation and crop-N uptake to ascertain the dangers of NO_3^- -N leaching and accumulation in plants under South African soil and climatic conditions.

Toxic organics

The most commonly encountered toxic organic compounds in the sewage sludge are, as follows: pesticides, polychlorinated biphenyls (PCBs), halogenated aliphatics, ethers, phtalate esters, monocyclic aromatics, phenols, polycyclic aromatic hydrocarbons (PAHs) and nitrosamines (Sommers and Barbarick, 1986). Generally the concentration of most organics does not exceed 10 mg.kg^{-1} (dry mass), although elevated levels of specific compounds are possible where an industry is discharging a specific compound into the sewage system. Because of the difficulty involved in assessing the eco-toxicity of the organic compounds in sewage sludge, no statutory limits on the levels of toxic organics have yet been established. The proposed threshold levels for sewage sludge content of the PCB is 2 mg.kg^{-1}. (Brümmer, 1989). Recent disclosure of the presence of highly carcinogenic dioxins in the sludge resulted in the banning of the application of sludge on pastural land in Germany (Strauch, 1989).

The health hazards posed by the toxic organics in sludge depend, to a large extent, on the extent to which these compounds are altered and attenuated upon the introduction into the soil system. After application to cropland, the fate of the compounds is controlled by several physical, chemical and biological processes. These include, *inter alia,* processes such as volatilisation, photodecomposition, microbial decomposition, adsorption, leaching into ground water, runoff into surface water and plant uptake (Overcash, 1983; Overcash and Pal, 1979). Because of the complexity of the chemical, physical, and biological interactions between the toxic organics and the soil constitutents, it is difficult to generalise about the rate and extent of transformations of these compounds in the soil environment.

A recent comprehensive investigation conducted by the US EPA (1985) indicates that the organics do not, in general, pose a threat to the soil biota, plants and animals. However, major potential problems may arise from the contamination of plant or animal products derived from the sludge-amended soil, and from direct soil ingestion by grazing animals. Furthermore, recalcitrant organic compounds accumulate in the soil environment, as evidenced by the recent findings in Germany where, following long-term application of sewage sludge, the level of the toxic organic compounds in soil exceeded their level in the sludge by a factor of 5 to 15 (Strauch, 1989). The potential health hazards resulting from the long-term application of low levels of toxic organic ompounds have not yet been evaluated.

Heavy metals

In the past 20 years, a large amount of research on heavy metals-soil interaction and plant uptake has been conducted. This may be attributed, in part, to the relative ease of the analytical determination of the metals in sewage sludge, soil and plant tissue, as opposed to the difficulty involved with the determination of the trace amounts of the toxic organic compounds. In general, soil-metal reaction appear to be well understood. There appears to be, however, considerable uncertainty about the factors controlling plant uptake of the metals and the associated problem of the transmission to animals and humans. A summary of the research findings on these factors is presented.

Toxic heavy metals, in particular Cd, Cu, Mo, Zn, Co, Ni, Pb nd Cr are frequently present in high concentrations in sewage sludge. 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. In particular, Cd, because of its relatively high mobility in the soil environment, is considered to be the element most likely to limit application of sludge on land (Page and Chang, 1981). Other limiting heavy metals are Zn, Ni and Cu, because of their phytotoxicity, and Mo because of its toxicity to livestock (CAST, 1976). With respect to the danger of transmission of heavy metals to the food chain, phytological and environmental factors may prevent their accumulation in plant tissue to levels that could be harmful to humans and animals. This "soil-plant barrier" (Sommers and Barbarick, 1986) applies to the elements Zn, V, Fe, Cr, Ni, Pb, B, and As (the last two are amphoteric elements), but fails in the case of Cd, Co, and Mo, which may therefore accumulate to toxic levels in plant tissue. The maximum permissible levels of some of the heavy metals in plant tissue and in the forages for domestic animals are shown in Table 2.

The results of a recent survey on the concentrations of heavy metals in South African sludges, as well as the current EEC norms for the maximum allowable concentrations of the metals in sludge for agricultural applications, are shown in Table 3. The large range of values for the different metals and sludges is indicative of the extremely variable composition of the sludge. Although the concentration of heavy metals in most of the sludges surveyed is lower than the maximum recommended limits, only a 63,6% of sludges surveyed meet the minimum recommended values for the metals (Smith and Vasiloudis, 1989).

Regulations of the US EPA as well as those of the European Community restrict the total cumulative amounts of heavy metals and annual application rates on soils. These rates depend, in particular, on the soil pH, the soir organic matter content and the soil cation exchange capacity. Provisional guidelines and norms for sewage sludge disposal on agricultural land in the RSA have been prepared (Vivier *et al.,* 1988). The recommended values for the maximum allowable concentrations of heavy metals in soil and the maximum allowable annual rates of application for the RSA and for the EEC countries are shown in Table 4. The South African norms were based on information obtained from the standards of the European Community (Webber *et al.,* 1984; CEC, 1986) and the results of limited field studies were conducted in the Cjape Province by the Division of Water Technology, CSIR (Kitshoff *et al.,* 1988). However, the validity of these norms for a large variety of soil and climatic conditions encountered in the RSA has not yet been established.

TABLE 2
MAXIMUM TOLERABLE LEVELS OF DIETARY MINERALS FOR DOMESTIC LIVESTOCK IN COMPARISON WITH LEVEL IN FORAGES

Element	"Soil Plant Barrier"	Phytotoxic level	Maximum level chronically tolerated (mg.kg^{-1} dry weight)			
			Cattle	Sheep	Swine	Chicken
Cd	Fails	5 - 700	0,5	0,5	0,5	0,5
Co	Fails?	25 - 100	10	10	10	10
Mo	Fails	100	10	10	20	100
Se	Fails	100	(2)	(2)	2	2
Cu	Yes	25 - 40	100	25	250	300
Mn	?	400-2000	1000	1000	400	2000
Ni	Yes	50 - 100	50	(50)	(100)	(300)
Pb	Yes	---	30	30	30	30
Zn	Yes	500-1500	500	300	1000	1000

Source: Logan and Chaney, 1983

TABLE 3
CONCENTRATIONS OF SELECTED HEAVY METALS IN SOUTH AFRICAN SEWAGE SLUDGE AND RECOMMENDED VALUES (EEC)

Province	Cd	Cr	Cu (mg.kg^{-1})	Pb	Ni	Zn
Free State						
Range	1,0-10	25-364	134-747	67-1360	13-63	548-3143
Mean	4,1	108	310	341	40	1458
Median	3,0	71	212	166	44	1327
Transvaal						
Range	1,0-112	107-10015	80-2147	113-949	41-2660	97-17680
Mean	21	989	535	370	289	2817
Median	6	506	352	299	93	1886
Natal						
Range	2-6	77-872	209-879	163-533	37-246	607-3482
Mean	4	287	379	292	92	1829
Median	4	177	298	213	80	1517
Cape						
Range	1-122	49-2240	129-17217	70-10137	6-181	237-5021
Mean	8	243	975	632	48	1370
Median	3	117	381	198	37	1025
EEC*	20-40	-	1000-1750	750-1200	300-400	2500-4000

Source: Smith and Vasiloudis, 1988.* Source: CEC, 1986.

TABLE 4
MAXIMUM PERMISSIBLE CONTENT OF HEAVY METAL IN SOIL AND MAXIMUM RATES OF APPLICATION (*M* AND *R*, RESPECTIVELY) FOR THE RSA AND THE EEC

Metal		RSA+ (mg kg^{-1})	EEC* (mg kg^{-1})	RSA+ (kg.ha^{-1}.yr^{-1})	EEC* (kg.ha^{-1}.yr^{-1})
Cadmium	Cd	2	1-3	0,160	0,150
Cobalt	Co	20	-	0,800	-
Chromium	Cr	80	-	22,0	-
Copper	Cu	100	50-140	6,0	12,0
Mercury	Hg	0,5	1-1,5	0,080	0,100
Molybdenum	Mo	2,3	-	0,200	-
Nickel	Ni	15	30-75	1,6	3,0
Lead	Pb	56	50-300	2,0	15,0
Zinc	Zn	185	150-300	22,0	30,0

+Source: Vivier *et al.,* 1988. *Source: CEC, 1986.

With respect to the transfer of heavy metals from soil to crops, recently-obtained data summarising the results of the 24 long-term field studies conducted in the Federal Republic of Germany, UK and Denmark are shown in Table 5. In this table various crops have been classified according to their ability to accumulate heavy metlas from sewage sludge applied to land. The values of soil-plant factor, *f*, (defined as a ration M_p/M_s, where M_p stands for the concentration of the element in the plant tissue, and M_s stands for its concentration in the soil) ranged from 0,01 to 10. In general, the highest *f* values were obtained for the element Cd, and the lowest for the elements Pb and Cr. The table indicates that, in general, grain, tuber and roots crops (except maize) can be grown on Cd-polluted soil, whereas green vegetables and fodder crops (except ryegrass) may accumulate Cd ($f < 1,0$). Similar results are found for Zn. In contrast, for the elements Cu, Ni, Cr and in particular Pb, most of the *f* values were lower than 1,0, indicating a low level of metal accumulation. The *f* values presented in Table 5 should be interpreted with caution, since they may depend on soil properties and the degree of soil contamination (Sauerbeck and Styperek, 1988).

Soil pH is the main factor controlling the mobility of heavy metals and their availability to plants. For the cationic species (Cd^{+2}, Cu^{+2}, Ni^{+2}, and Zn^{+2}) the availability tends to decrease with increasing pH, since the insoluble phases of these metals are more stable at higher pH values (Lindsey, 1979; Brümmer *et al.,* 1986). The pH effect is not always apparent because of the confounding effects of factors such as chelation by organic soil constituents and the slow rate of reactions, all of which are also dependent on pH (Emmerich *et al.,* 1982a,b). Nevertheless, a general rule of thumb is that soils should be limed to pH 6,5 to reduce heavy metal availability (US EPA, 1983). For the elements that exist primarily in the anionic form in the sludge (Mo, As, and Se) the availability should, theoretically, be increased with increased pH. Hence, overliming may pose a danger of an increased toxicity of these elements. Under South African conditions this is seldom a limitation because of the prevalence of the acidic soils.

An additional hazard of sewage sludge is the threat of a potential contamination of surface waters with nutrients and heavy metals following sewage sludge application. Studies have shown that runoff water and eroded soil sediments from sewage sludge treated land may contain excessive amounts of phosphate, nitrates, and toxic heavy metals (Deizman *et al.,* 1989; Klavidko and Nelson, 1979). This suggests that the contaminants present in sewage sludge may be translocated to the water courses. In South Africa this would present a serious health hazard, since most of the drinking and irrigation water is derived from the surface water reservoirs. Furthermore, the extent of runoff and erosion of agricultural lands in South Africa is much higher than in temperate climates. In order to prevent potential surface water contamination with sludge constituents it is generally recommended that the maximum slope of the site of application should not exceed 6% (Vivier *et al.,* 1988).

In spite of these potential pollution hazards, overseas literature seems to indicate that sludge application does not, in general, result in the accumulation of heavy metals in crops grown on sludge-amended soil. The general consesus appears to be that, provided that soil pH is kept above 6,5 and the recommended rates of application are strictly observed, heavy metals should not present a health hazard. A proper supervision of the application site, including measures such as periodic sampling of sludge, soil and plant material should, however, be required in order to monitor the heavy metal accumulation. The costs of such environmental monitoring should be considered in assessing the economic feasibility of sludge disposal on agricultural land in South Africa. Furthermore, the present lack of manpower may limit the opportunities for such site surveillance. It appears, therefore, that guidelines for sludge utilisation in agriculture in South Africa should be significantly more conservative that those of the Western countries, in order to allow for the lack of site monitoring and the associated potential health hazard problems.

Conclusions

Sewage sludge is a valuable resource material, used as a fertiliser and a soil conditioner by farmers in many countries in the Western world. The main benefits of sludge application to the farmer are: provision of major plant nutrients (in particular N and P), increased supply of some of the essential micronutrients (in particular Zn, Cu, Mn and Mo) improvement in the soil structure, and increased soil water-holding capacity. Sludge can generally be considered as low analysis, slow-release fertiliser material which can be used as a maintenance fertiliser on perennial crops, e.g. sugar-cane, fruit trees and grasses. It can be of particular benefit in cases where the availability of nutrients from commercial inorganic fertilisers is

TABLE 5
HEAVY METAL TRANSFER FACTOR (*f*) FOR VARIOUS CROPS

f^+ value	Cd	Zn	Ni	Cu	Pb	Cr
0,01-0,05	cereals maize potatoes	potatoes	cabbage (white) carrot celery cereals leeks lettuce maize spinach sugar beet	celery cereals leeks maize	cabbage (green) cabbage (white) carrot celery cereals leeks lettuce maize spinach sugar beet	cabbage (white) carrot celery cereals leeks lettuce maize spinach sugar beet
0,5-1,0	cabbage (white) leeks sugar beet	cabbage (white) celery cereals leeks		cabbage (green) potatoes spinach		cabbage (green)
1,0-2,0	cabbage (green) celery	maize sugar beet	cabbage (green)	lettuce sugar beet		
2,0-10	carrot lettuce spinach	cabbage (green) carrot lettuce spinach		carrot		

$^+f = [M]_p/[M]_s$; ([M] - metal concentration; p, s subscripts refer to plant and soil, respectively). Source: Sauerbeck and Styperek, 1988

low due to factors like high leaching losses (in the case of NO_3^-), or high soil-P fixing capacity.

In spite of the proven benefits of sewage sludge application, its use in agriculture is limited by factors such as the presence of pathogenic organisms, nitrate contamination of ground water, toxic organics, and heavy metal transmission in the food chain. Of these factors, the transfer of heavy metals and pathogenic organisms from soil to crops, grazing animals and humans, appears to be the greatest potential health threat. Consequently, most of the existing guidelines for sludge application on land limit the amounts of sludge that can be applied on land, according to their heavy metal content (in particular the content of Cd) and the presence of certain pathogenic organisms. The data appear to support the view that the risk of heavy metal transport to the food chain is minimal, provided that soil can be maintained at pH values above 6,5. This stipulation is a major limiting factor for sludge application on agricultural land in the RSA, where acid soils of pH values below 6,0 are ubiquitous. Maintenance of proper pH values, e.g. through application of liming materials, combined with adequate soil, plant, and water quality monitoring procedures are required to prevent potential health hazards of sludge application on agricultural land. Provided that these safety measures are maintained, application of sewage sludge on agricultural land can provide one of the major disposal routes for the increasing amounts of sludge being generated in the metropolitan centres in South Africa.

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