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DRIED GAMMA-IRRADIATED SEWAGE SOLIDS USE ON CALCAREOUS SOILS: CROP YIELDS AND HEAVY METALS UPTAKE[1/]

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INTRODUCTION

The increasing volumes of sewage sludge and treated municipal wastewater (sewage-effluent) have put pressure on cities to utilize or dispose of these materials. One of the most readily available and cheapest means of utilizing and disposing of these wastes is by application to crop land. The beneficial effects of land application of sewage products have been known at least since the early use by Greek and Roman farmers as is indicated by writings of Theophratus (372-287 B.C.). Now sewage products are appreciated for their nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn) contents as well as for other trace elements and organic matter. However, with increasing industrialization and modernization, heavy metals and other toxic materials have been allowed to contaminate municipal sewage materials, and it is becoming increasingly apparent that land applications of sewage must be restricted to levels that will prevent ground and surface water pollution and prevent buildup of toxic materials in the environment (3, 11, 13, 18, 23, 30-35, 52, 54, 55, 57).

There has been an increase in number of books and articles published in the last four or five years giving information on most aspects of cropland utilization of sewage such as fertilizer value, crop dry-matter production; plant tissue concentrations of nutrients and toxic materials; optimum sludge application rates relative to sludge composition and soil parameters; land reclamation; and phytoxicity problems related to nutrient imbalance and increased plant uptake of heavy metals. The greatest risks from cropland utilization of sludge has been indicated to be the potential introduction of toxic levels of heavy metals and/or viable pathogens into the human food chain. Burge and March (9) recently

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reviewed the literature relating to infectious disease hazards of land-spreading of sewage wastes and indicated that much evidence indicates that processed sewage wastes, including chlorinated effluents and digested sludges, still contain viral, bacterial, protozoan and helminthic agents of disease. They also point out that the great majority of illnesses associated with sewage, appears to have been caused by application of raw or inadequately treated sewage materials to crops which were consumed raw; by contamination of private water supplies from septic systems; and by consumption of raw shellfish grown in sewage polluted waters. They then indicate that the greatest hazard for movement of pathogens from land application results from surface runoff and that the evidence examined shows little danger either to workers or people of surrounding communities when chlorinated sewage materials are used for irrigation or when anaerobically digested sludges or pathogen reduced sludges are applied to soils for production of crops not to be consumed raw by humans. However, they go on to conclude the following:

> "Regulations now in force in the United States usually prohibit the use of raw sewage on growing crops and provide that partially disinfected effluents shall not be used to water food crops to be consumed raw. The question of how long land treated with anaerobically digested or partially disinfected sewage wastes should remain out of food production of food crops for consumption raw is currently being debated. The time adopted will probably be not less than a year, possibly much longer. Most pathogens will die or be at very low numbers in a year's time, although Ascaris ova may remain viable in soil much longer. Whether such ova can be a significant source of infection after a year needs to be determined." (9)

A number of alternatives exist for further treatment of sludge-carried pathogens surviving primary sewage treatments (anaerobic digestion, aerobic digestion, chlorination, etc.), such as air or mechanical dewatering, pressure-heat treatment, incineration and heat drying. Heat treatments result in complete inactivation of pathogens but pose air pollution and high energy consumption problems (52).

The use of nuclear reactor wastes as a radiation source to kill pathogens in sewage sludge has been studied at Sandia Laboratories, Albuquerque, New Mexico, and is adding a new dimension to sludge utilization in the United States. The use of ionizing radiation for the destruction of pathogens in sewage has been reviewed by many including Gerrard (22), Ballentine (2) and Reynolds (52). The radiation process being developed at Sandia uses cesium-137 separated from nuclear ~~power industrial~~ wastes and has a favorable cost/benefit potential outlined by Morris (47). Cesium-137 is a source of energetic (660 Kev) gamma rays, sufficiently energetic to kill pathogens but of much lower energy than required to induce radiation in the sludge itself. The cesium-137 process has been shown to be very effective in reducing sludge-carried pathogens numbers to very low levels, including especially Ascaris ova (Sivinski, 57). Sludge treated with gamma radiation offers considerable potential for use as a fertilizer in agriculture or as a soil conditioner for land reclamation, since it is free of the potential pathogen hazard associated with conventional methods of land disposal (52, 53, 56, 58).

Heavy metals transferred to the soil-plant system have received much study, particularly when applied to acid soils. The concentrations of plant-available metals found in sewage sludges are frequently higher than the concentrations found in soils, and some of these metals, which are toxic to plants or animals, are potentially available to the crop growing on sludge-treated soil. The greatest concerns in the United States have been focused on cadmium, its subsequent movement into the food chain, and the associated public health and environmental problems (4-7, 10, 14-21, 24, 26-30, 37, 39, 42, 44-46). Since it is well known that most of the metals are less of a problem on neutral to high pH soils than on acid soils, it is generally recommended that the sewage-sludge amended soil be maintained at a near-neutral or higher pH (12). However, little information is available about the effect of sewage-sludge application of trace elements or heavy metals in calcareous soils having constantly higher than neutral pH's.

Cropland utilization of sludge using calcareous soils (above neutral pH) and gamma-radiation treatment greatly reduces the major two risks (pathogens and heavy metals) to the human food chain. In addition, approximately 1.4 million hectares (ha) of southwestern United States soils are deficient in various plant-available metals that are essential plant micronutrients. The problem is especially acute with iron in these soils due to high pH, lime and bicarbonate contents (48). Also, zinc, manganese and copper have been shown to be deficient. Sewage-sludge or sewage-effluent could represent a great potential for adding metals to the deficient areas.

The general Beneficial Uses Program is a joint Department of Energy/Environmental Protection Agency effort whose objective is to utilize beneficially the isotope cesium-137 and the rapidly increasing amounts of sewage sludge being generated as we clean up our wastewater discharges. The isotope is used to irradiate the sludge to reduce pathogens so that the sludge can be used effectively in unlimited agricultural applications[4/]. Studies[5/] underway indicate that social, economic, public health and technical pressures are resulting in searches for better methods of disposal or utilization which are less polluting, energy and resource conservative and which recognize recycling as a matter of great importance in a food-hungry world.

4/ Sivinski, H. D., "Treatments of Sewage Sludge with Combinations of Heat and Ionizing Radiation (Thermoradiation)," Proceedings of the International Symposium on the Use of High-Level Radiation in Waste Treatment, Munich, IAEA-SM-194/303, March 1975.

5/ Report on Technical and Economic Factors in the Beneficial Use of Radiation in Municipal Sludge Management, SAND77-7029, November 1977, Sandia Laboratories, Battelle-Pacific Northwest Laboratories and Arthur D. Little, Inc.

This paper is a summary of four series of experiments designed to examine gamma-radiation effects on extractable and plant-available sludge elements and to examine the response of crops to sludge applications on two typical, calcareous soils in New Mexico. Some of the data presented herein have been published previously, as noted by references.

METHODS

Experiment 1

Characterization of Sludge Products. Methods and Results of Experiment 1 are a summary from McCaslin and Titman (41). Approximately 400 gallon liquid samples of both undigested (raw sewage as it entered the treatment plant) and anaerobically digested sewage sludge (after secondary sewage treatment) from the Albuquerque, New Mexico Sanitation District were collected and each thoroughly mixed and then divided into halves. One-half of each of the digested (DSS) and undigested (USS) sludge samples were radiation treated (RDSS and RUSS, respectively); the other half of each sample of sludge was left untreated. The sludges were air dried and shipped to New Mexico State University.

Sewage sludges for chemical analysis were air dried in a forced air oven (25°C) and ground to pass a 10 mesh screen in a stainless steel Wiley Mill. The ground samples were analyzed for total nitrogen according to Bremner (8) and organic carbon content by the Walkley-Black method, Allison (1). Sludges were prepared for mineral analysis by nitric + perchloric acid wet digestion (51) and for analysis of water-soluble elements by mixing deionized water with 50 grams of sludge until an approximate saturation paste was obtained using 150 percent water by weight for digested sludge and 250 percent water by weight for undigested sludge. Saturation pastes were equilibrated for 24 hours and suction filtered. Sludges were prepared for DTPA-extractable metals determination by shaking 25 grams of sludge with 150 ml DTPA extractant for 2 hours (30). For 0.1 N, HCl extractable metal determination sludges were prepared by shaking 2 g sludge with 100 ml 0.1 N HCl for 2 hours. Saturation extracts, nitric-perchloric digests, HCl extracts and DTPA extracts were analyzed for Fe, Cu, Mn, Zn, Pb, Cr and Cd by atomic absorption spectrophotometry.

Plant Available Sludge Elements. A greenhouse experiment with 11 treatments (Table 1) in a five replication randomized block design was established. Each of the sludges was added to soil at rates to supply 500 and 1000 pounds of elemental N per acre. An untreated soil and two commercial fertilizer treatments of 112 kg N/ha plus 45 kg P/ha and 224 kg N/ha plus 90 kg P/ha were included as checks in the experiment. Fertilizers or sludges were thoroughly mixed with 7.7 lbs (3.5 kg) soil and placed in plastic 7 inch (17.8 cm) pots with drainage holes in the bottom. The soil used in the experiment was a surface [0-12 in (30 cm)] sample of clay loam soil (Torrifluvent) from the New Mexico State University Plant Research Center (Table 2). Eight sorghum seeds were planted in each pot and thinned to 3 plants at 2 weeks. Plants were

Table 1. Treatment description and amount of fertilizer or sludge added in each treatment for 2-month greenhouse experiment.*

Treatment Description	Amount of Sludge or Fertilizer Added to 3.5 kg Soil	Comparable Amount of Sludge or Fertilizer Added per Land Area Basis
Check	0	0
100-40-0	.389 g urea .152 g superphosphate	222 lb/acre urea (249 kg/ha) 87 lb/acre superphosphate (97 kg/ha)
200-80-0	.778 g urea .304 g superphosphate	444 lb/acre urea (497 kg/ha) 174 lb/acre superphosphate (195 kg/ha)
USS - 500 lb N/A (560 kg/ha)	32.423 g	9 ton/acre (20.2 metric ton/ha)
USS - 1000 lb N/A (1120 kg/ha)	64.847 g	18 ton/acre (40.3 metric ton/ha)
TRUSS - 500 lb N/A (560 kg/ha)	32.423 g	9 ton/acre (20.2 metric ton/ha)
TRUSS - 1000 lb N/A (1120 kg/ha)	64.847 g	18 ton/acre (40.3 metric ton/ha)
DSS - 500 lb N/A (560 kg/ha)	51.496 g	15 ton/acre (33.6 metric ton/ha)
DSS - 1000 lb N/A (1120 kg/ha)	102.992 g	30 ton/acre 67.2 metric ton/ha)
TRDSS - 500 lb N/A (560 kg/ha)	51.496 g	15 ton/acre (33.6 metric ton/ha)
TRDSS - 1000 lb N/A (1120 kg/ha)	102.992	30 ton/acre (67.2 metric ton/ha)

*Table is from McCaslin and Titman (41).

Table 2. Chemical properties of soil used in 2-month greenhouse experiment.*

E.C. mmhos	pH	Organic Matter %	NO_3^- ppm	P ppm	K ppm	$CaCO_3$ %	Fe ppm	Cu ppm	Mn ppm	Zn ppm	CEC meq/100g	Sand %	Silt %	Clay %
4.05	7.57	.53	26	19	448	7.5	7	3	7	8	21	29	34	37

*Table is from McCaslin and Titman (41).

grown with natural illumination in a greenhouse for approximately two months, September 25 to November 19, 1976. Pots were watered by hand to approximately 90 percent of field capacity twice weekly. Plants were harvested from the soil surface, washed, dried at 70°C and weighed. Three replicate plant tissue samples were analyzed for total nitrogen as in Bremner (8) and digested with nitric + perchloric acid and analyzed for P, K, Fe, Cu, Mn, Zn, Cr, Cd and Pb. After plant harvest soil samples were taken from the surface to the bottom of the pot, air dried, sieved (2 mm) and analyzed for extractable P, K and exchangeable NH_4 and NO_3^-, pH, electrical conductivity and DTPA extractable Fe, Mn, Zn, Cu, Cd, Pb and Cr.

Experiment 2

Sludge. Methods and Results of Experiment 2 are a summary from McCaslin and Rodriguez (40). Anaerobically digested sewage sludge sampled after secondary sewage treatment from the Albuquerque, New Mexico Sanitation District plant was collected by Sandia Laboratories and irradiated with 150 Krad of gamma-radiation. In the laboratory, the RDSS was dried at 25°C in a forced air oven, ground and stored in a plastic barrel.

Soils. The soil used in experiments 2 and 3 was from Lea County, New Mexico, approximately 25 kilometers northeast of Lovington, New Mexico. The Lea soil was classified as a fine-loamy, mixed, thermic Petrocalcic Paleustoll and was known to be severely iron-deficient. Sorghum plants growing in the soil typically develop iron chlorosis symptoms very early (7 to 10 days after germination) and usually die 20 to 25 days after germination. Bulk samples of this soil were obtained randomly from the 0-25 cm depth. The soil was air dried, crushed to pass a 5-mm sieve and stored in plastic barrels.

Experimental Design. This experiment was designed to study the potential phytotoxicity problem of RDSS and its micro-nutrient fertilizer value, through three successive plantings of grain sorghum. The nine treatments selected are presented in Table 3. For the first planting, the RDSS was applied at constant increments of 10 metric ton/ha, up to 50 metric ton/ha on the surface area basis. The treatments included as checks were: 1) untreated soil, 2) soil ratio 2:1 (soil/RDSS) by dry weight, 3) pure RDSS, and 4) commercial fertilizer 200 kg N/ha. The normal rate of N recommended for sorghum in the Lovington, New Mexico, area is 170 kg/ha. The RDSS and fertilizer (urea) were thoroughly mixed with 2 kg of soil and placed in a plastic pot (open top equals 17 cm, base equals 11 cm and height equals 17 cm), with drainage holes (gravel was added) in the bottom. Ten grain sorghum seeds were then planted in each pot and thinned to two plants at five to seven days after germination. Plants were grown with natural illumination in a greenhouse for ten weeks, from October 29, 1976, to January 8, 1977. Pots were watered to approximately 90% of field capacity as determined by pressure plate at 1/3 bar, initially once, and later twice per week.

Table 3. Treatment description in greenhouse experiment 2.

Treatment	Amount of RDSS or Fertilizer Added to 2 kg Soil
Soil only	0
RDSS 10 metric ton/ha	16.51 g RDSS
RDSS 20 metric ton/ha	33.02 g RDSS
RDSS 30 metric ton/ha	49.54 g RDSS
RDSS 40 metric ton/ha	66.05 g RDSS
RDSS 50 metric ton/ha	82.56 g RDSS
RDSS 381.5 metric ton/ha Radio 2:1 (soil/RDSS)	630.00 g RDSS
Pure RDSS (no soil)	1,260.00 g RDSS
200 kg N/ha	0.72 g RDSS

Plants were harvested at the soil surface, oven dried at 65°C in a forced-air oven and weighed to determine total dry weight yields. Ground plant tissue samples were stored in sealed plastic bags for later chemical analysis. After plant harvest, soil samples were taken from each pot, air dried, sieved (2-mm) and thoroughly mixed. They were stored in sealed plastic bags for later chemical analysis.

The nine treatments selected were established in a randomized complete block design, with four replications. Plant tissue for each treatment and replication (with the exception of soil-only and fertilizer treatments which were pooled over replications) were thoroughly mixed, and the chemical determinations were the same as in experiment 1.

After collecting soil samples from each pot from the first planting, the soil surface was mixed to loosen the surface as if by tillage for the second planting period (from January 14 to March 25, 1977), using the same grain sorghum variety and without appliction of the treatments. The same watering, sampling and analysis procedures for plant and soil, etc., were used as described for the first planting. For the third planting period (from April 3 to June 13, 1977), the same procedures used for the second planting were followed.

Experiment 3

Experimental Design. This experiment was designed to evaluate the efficiency of RDSS as a soil-applied iron fertilizer. The soil used (Lea soil) was the same as was used in Experiment 2. The 14 treatments selected are presented in Table 4. The RDSS rates were applied at constant increments of 10 metric ton/ha, up to 40 metric ton/ha, based on the results of Experiment 1. Fertilizer Fe was added in the form of iron chelate, active ingredient technical sodium ferric ethylenediamine di-(hydroxyphenylacetate). The compound is sold commercially as "Sequestrene 138 Fe" (S-138 Fe) and contains six percent Fe by weight. The distributors recommend applying up to 5.6 kg/ha of commercial (S-138 Fe) material at planting or when deficiencies first appear. However, due to the severely Fe-deficient nature of the Lea soil, the iron treatments were applied at constant increments of 10 kg/ha, up to 30 kg/ha of S-138 Fe, plus an additional high-iron treatment of 5 kg/ha of elemental iron (equal to 83.34 kg/ha of S-138 Fe). The 83.34 kg/ha of S-138 Fe would not be economically feasible to use, for its cost would be around $3,000 per hectare; however, the treatment was included for comparison purposes. All the iron treatments were applied with and without the application of the N-P fertilizer treatment. An untreated soil and one N-P fertilizer treatment alone (240 kg N plus 50 kg P_2O_5/ha) were included as checks. Since the amounts of S-138 Fe used were very small, each iron treatment was mixed with small amounts of the same soil (8 to 10 g), passed through 60-mesh screen, and mixed uniformly into each pot at planting time. The RDSS or fertilizer (urea and superphosphate materials) were thoroughly mixed with 2 kg of soil (Lea soil)

Table 4. Treatments in Experiment 3.

Treatments	Amount of RDSS or S-138 Fe Added to 2 kg of Soil	Amount of Iron[a] (Fe) Added Per Hectare
Soil only	-	-
RDSS 10 metric ton/ha	16.51 g	134.06 kg
RDSS 20 metric ton/ha	33.02 g	268.12 kg
RDSS 30 metric ton/ha	49.54 g	402.18 kg
RDSS 40 metric ton/ha	66.05 g	536.24 kg
F[b]	0.90 g urea + 0.18 g superphosphate	-
S-138 Fe-10 kg/ha + F	0.016 g + F	0.60 kg
S-138 Fe-20 kg/ha + F	0.032 g + F	1.20 kg
S-138 Fe-30 kg/ha + F	0.048 g + F	1.80 kg
S-138 Fe-83.3 kg/ha + F	0.137 g + F	5.00 kg
S-138 Fe-10 kg/ha	0.016 g	0.60 kg
S-138 Fe-20 kg/ha	0.032 g	1.20 kg
S-138 Fe-30 kg/ha	0.048 g	1.80 kg
S-138 Fe-83.3 kg/ha	0.137	5.00 kg

[a]Based on the RDSS total Fe concentration (13405 µg/g) and S-138 Fe equals Sequestrene 138 Fe, 6% elemental Fe.

[b]F equals N-P_2O_5-K_2O (250-50-0) g/ha.

and placed in a plastic pot (open top equals 17 cm, base equals 11 cm and height equals 17 cm) with drainage holes in the bottom. Ten grain sorghum (Sorghum bicolor var. Capitan) seeds were planted in each pot and thinned to two plants at 5 to 7 days after germination. Plants were grown with natural illumination in a greenhouse (different from Experiment 1) for 10 weeks, from September 16 to November 24, 1977. The watering and sampling procedures were the same as described for the first planting in Experiment 2.

The plant tissue for each treatment and replication (with the exception of treatments: soil alone, fertilizer and 10, 20 and 30 kg/ha of S-138 Fe with and without fertilizer, which were pooled over replications), were thoroughly mixed, and laboratory determinations were the same as in plant material for Experiment 1. In order to compare the 14 means, the analysis of homogeneity of variances was done using the Bartlett's test After sorghum harvest, soil samples from each plot were collected and analyzed for DTPA-extractable Fe, Zn and Mn.

Experiment 4

Site Description. Methods and Results of Experiment 4 are a summary from McCaslin and Rodriguez (39). Fields were located that had been irrigated for forty years only with secondary sewage effluent from the city of Clovis, New Mexico (population approximately 29,000). Application rates were not recorded over the years. However, at least a minimum of 0.81 m per year had been used and required for full crop production. Adjacent fields were located that had never been irrigated with sewage effluent.

Soils. Adjacent and comparable fields from the Clovis area were selected, one of which had been irrigated with secondary sewage effluent for approximately forty years and the other field for forty years with ground water. From each site, five (5 cm diameter) columnar soil samples were collected to a maximum depth of two meters with hydraulic, truck-mounted sampler.

Effluent. Secondary sewage effluent from one of the irrigation lateral canals was sampled at nine different times during a 24-hour period. Two effluent samples were taken at each time, giving a total of 18 samples. In the field, each sample was immediately placed on ice for transport to the laboratory. In the laboratory one sample from each sampling time was treated with sulphuric acid (H_2SO_4) and the other with nitric acid (HNO_3) in order to keep the pH between 2 and 3 to help prevent precipitation of metals. They were then placed in refrigerator storage for subsequent chemical analysis.

Plant Material. In the fall of 1976, six random representative corn (Zea mays) and grain sorghum samples were collected from each Clovis field soil sampled; each corn sample consisted of a composite of three corn plants randomly selected. The entire above ground portion of the plant at approximate physiological maturity was sampled. The next season, wheat (*Triticum aestivum*) tissue samples were taken from the same fields consisting of five composite and randomly-selected samples taken at the early boot stage of growth.

In the laboratory each plant sample was washed gently with mild detergent and rinsed with glass-distilled deionized water and corn samples were separated into leaf and stem. Then all plant material samples were dried at 65°C for 48 hours in a forced-air oven and ground in a Wiley mill equipped with stainless steel blades to pass a 40-mesh screen. Ground samples were stored in paper ice cream containers for subsequent chemical analysis.

Plant samples were thoroughly mixed, then from each sample (leaves or stem), triplicate one gram samples of plant material were digested using the wet ash (predigestion with nitric acid overnight, followed by three or four hours perchloric acid digestion) method (51). The concentrations of Fe, Zn, Mn, Cu, Cd, Cr, Ni and Pb in the diluted digest were determined by atomic absorption spectrophotometry.

RESULTS AND DISCUSSION

Experiment 1

Chemical Composition of Sludges. The total analyses of the dried sludges used in the study show a difference in nutrient concentration in N, organic carbon, pH, electrical conductivity, C/N ratio, Pb, Cd, Cr, Fe, Zn, Cu and Mn between undigested (USS) and the anaerobically digested sewage sludes (DSS) (Table 5). The radiation process had no detectable effect on concentration of chemicals, and the differences in chemical concentration between digested and undigested sludges is partially confounded by different sampling times.

Data are not given here but analysis of variance (F-test at 5% level) for the triplicate extracts for heavy metals from both digested and undigested sewage materials indicated no significant increases in extractable metals resulting from the radiation treatment for the extractants HCl, DTPA and H_2O. However, the HCl Zn and Cd in the digested sludge was approximately 93 percent of the total Zn and Cd, compared to 69 and 72 percent of the total Zn and Cd, respectively, in the undigested sewage. The three extractants were selected to give three degrees of strength of extractability and did not necessarily represent plant available heavy metals.

Effect of Radiation on Plant Nutrient Availability. Significantly more sorghum dry matter was produced in all undigested sewage sludge treatments and in the 67.2 metric ton/A rates of the digested sewage

Table 5. Total analysis of undigested (USS), irradiated undigested (RUSS), digested (DSS) and irradiated digested (RDSS) sewage sludges collected at the Albuquerque, New Mexico Sanitation District.**

Sludge Type	Comm. Fert. Value for N	P_2O_5	K_2O	Org. Carbon	pH	E.C.* mmhos	C/N Ratio	Pb	Cd	Cr	Fe	Zn	Cu	Mn
	%					(cm)		ppm						
USS	2.8	2.0	0	30	5.9	5.0	11/1	626	15	194	10771	1364	852	145
RUSS	2.8	2.3	0	30	5.8	4.9	11/1	608	14	194	10864	1333	796	143
DSS	1.9	2.4	0	15	6.5	8.1	8/1	678	26	379	14671	1684	1132	236
RDSS	1.8	2.5	0	15	6.3	8.2	8/1	676	27	395	14857	1676	1121	234

*pH and E.C. are on approximate saturation extracts, 150% water by weight for digested sludge and 250% water by weight with undigested sludge.

**Table is from McCaslin and Titman (41).

than in the check treatments (Table 6). The two high rate (40.3 metric ton/ha) treatments of USS gave the highest yields, followed by the two high rates of DSS and the two low rates of USS. There was no significant difference between the two low rates of DSS and the checks. Also, no significant growth differences occurred between any corresponding radiation and untreated sludge treatments, indicating little or no effect from the radiation treatment in respect to growth response for sorghum.

The sorghum tissues were then analyzed to determine whether nutrient concentrations varied, thus testing whether radiation had significant effects on tissue elemental concentrations perhaps not displayed in plant growth differences. No significant increases in plant tissue elemental concentrations resulted from corresponding radiation treated and untreated sludges for the elements analyzed by orthogonal contrasts at the 5% level of significance. The total nutrient uptake (i.e., elemental concentration in tissue multiplied by the total dry matter yield) does indicate the effect of sludge applications on total heavy metals removed from the soil. The highest yielding treatments removed the most metals.

Since the application rate of each sludge was based on the nitrogen content of the sludge, the total amount of heavy metals added per pot varied with sludge type as well as with amount added. More metals were added per pot in the DSS treatments. Extractable soil Cu, Cd, Pb, Fe, Zn, Mn and P were significantly higher for the DSS treatments than for the USS treatments, but it should be remembered that more of these elements were added initially to the soil in the DSS treatments.

Experiment 2

Sludge. The RDSS used is characterized by having slightly acid reaction, almost 12 percent organic carbon content, with C/N ratio of 5/1 which is sufficiently narrow to obtain mineralization of nitrogen, a very high CEC compared to soil used, and a very high salt content. Most of the micro-nutrient and heavy metal total concentrations are in general agreement with RDSS values reported in Table 5, and would be typical of dried secondary treated sewage solids from the Albuquerque, New Mexico Sanitation District plant.

Plant Material. Sorghum plants growing in the RDSS-treated Lea soil were actively growing, deep green and healthy-looking plants. Plants in the pure RDSS and 2:1 (soil/RDSS) ratio treatments were dead in the first growth period, and some of them after the second growth period in the pure RDSS treatment only; probably mainly due to high salt levels indicated by high electrical conductivity values, greater than 5 mmhos/cm. But, at the third growth period, the plants in the pure RDSS treatment were the largest plants. Plants growing in the control soil and fertilizer treatment were stunted, light-green to yellow in color, and very unhealthy-looking plants, typical of iron deficiency. This symptom was more critical from one growth period to the next one.

Table 6. The average sorghum dry matter produced per sludge and fertilizer treatment after approximately 2-month growing period in greenhouse conditions.**

Treatment	Yield (g/Pot)
Check	.159c*
100-40-0	.142c
200-80-0	.242c
USS (9 ton/A)	1.770b
USS (18 ton/A)	2.973a
TRUSS (9 ton/A)	1.782b
TRUSS (18 ton/A)	2.443a
DSS (15 ton/A)	.554c
DSS (30 ton/A)	1.480b
TRDSS (15 ton/A)	.426c
TRDSS (30 ton/A)	1.438b

*Means followed by the same letter are not significantly different at the 5% level by the New Duncan's Multiple Range Test.

**Table is from McCaslin and Titman (41).

Total dry matter yields show significant RDSS effects for the successive plantings (Table 7). At the first harvest, yields showed a significant increase as the RDSS rates increased, up to 40 metric ton/ha and no yields were obtained at the 2:1 (soil/RDSS) ratio and pure RDSS treatments, probably due to the high salt contents as measured by electrical conductivity. The second and third harvest followed similar trends, as described for the first harvest, except that higher yields were obtained with 2:1 (soil/RDSS) ratio and pure RDSS treatments. The soil alone and fertilizer treatments produced the lowest yield.

The increase in yield after each successive planting indicated that the crops continued to respond favorably to RDSS applications; probably for at least three plantings after treatment, principally at the higher RDSS appliction rates. However, these rates may have supplied greater amounts of nutrients than were needed originally.

Chromium, Cd, Ni and Pb were not detectable in sorghum tissue digests even from the pure RDSS treatment <0.25 ppm. Iron concentration levels were not significantly affected by treatments at the first harvest (probably due to the large variation among replications). The levels at the second and third harvest were affected by some RDSS treatments, but there was no consistent trend. Concentrations from the first to the third harvest show a trend to decrease, particularly from the first to second harvest, which is similar to the trend followed by DTPA-extractable iron.

Zinc concentration levels in the first harvest were affected by RDSS treatments with tissue concentrations increasing as RDSS rates increased. The levels at the second and third harvests were affected in a similar manner as described for iron, except for pure RDSS treatment in which concentrations increased rather than decreased. Amount of DTPA-extractable soil zinc also tended to decrease after successive harvests for each treatment.

Manganese levels were either not affected or reduced by the RDSS treatments, except for an increase by the pure RDSS treatment in the second and third harvest. There was no significant effect of treatments on Cu level at any of the three successive harvests.

Iron, Zn, Mn and Cu concentrations obtained at all harvests were within the range normally found in plant tissue. They also were below the tolerance levels of metals for agronomic crops suggested by Melsted (43), with the exception of zinc at the third harvest in the pure RDSS treatment where the suggested level of 300 μg/g was exceeded by 52.55 μg/g.

In almost all plant tissue harvests soil only and pure RDSS treatment had similar, and the highest, concentrations of most of the elements but soil only produced lower total growth compared to other treatments except soil + fertilizer nitrogen.

Table 7. Sorghum dry matter production as affected by several rates of RDSS for each of the three successive harvests.*

Treatments	Harvest[a] 1st	2nd	3rd
	-----	g/pot	-----
Soil only	0.42d	0.27e	0.31e
RDSS 10 M.T./ha	1.41c	2.24cd	1.90d
RDSS 20 M.T./ha	2.18b	1.82d	3.06cd
RDSS 30 M.T./ha	2.04b	2.84bcd	3.36cd
RDSS 40 M.T./ha	2.78a	3.39bc	3.76cd
RDSS 50 M.T./ha	2.31ab	3.74b	3.91c
N 200 kg/ha	0.24d	0.21e	0.29e
2:1 (soil/RDSS)	--	8.12a	8.66b
Pure RDSS	--	1.97d	11.41a

[a]Means within each harvest followed by the same letter are not significantly different at the 5% level by Duncan's Multiple Range Test.

*Table is from McCaslin and Rodriguez (40).

Experiment 3

The objective was to evaluate the RDSS as a source of iron in a soil known to be severely iron-deficient. Dry yields, iron concentrations in plant tissue, plant uptake of iron and DTPA-extractable iron are given in Table 8. Sorghum plants growing in the RDSS treatments and in the highest S-138 Fe level (5 kg/ha active Fe), were dark green and healthy-looking plants. In the rest of the treatments the plants showed typical visual iron deficiencies in different grades, but there were more severely affected plants in the soil alone and fertilizer treatments.

Yields for all RDSS treatments, 20 metric ton/ha and higher, were significantly different from each other and significantly higher than the rest of the treatments. S-138 Fe treatments were not affected by the addition of N-P fertilizer. The highest S-138 Fe treatment (5 kg/ha elemental Fe) yield was not statistically different from the lowest RDSS level (20 metric ton/ha) and was significantly higher than the rest of the S-138 Fe treatments. Generally, yields tended to increase as the S-138 Fe rates increased. RDSS rates, however, showed significant increases with each RDSS treatment.

Iron concentrations in plant tissue were not affected by treatments probably due to the growth dilution effect. Iron uptake showed significant differences comparable to yields, and followed the same trend as a function described for yield.

Concentrations of DTPA-extractable soil iron resulting from the application of all RDSS treatments were significantly different from each other and significantly higher than the rest of the treatments. The highest S-138 Fe level (5 kg/ha elemental Fe) with or without fertilizer, and all RDSS rates were the only treatments which resulted in concentrations equal or above the sufficiency level (>5 ppm).

These data indicate the deficiency of available iron in the Lea soil and the superiority of soil-applied RDSS as a source of iron compared to S-138 Fe. The Fe-DTPA soil extractable iron values followed yield levels rather closely with a correlation coefficient of r equals 0.88 (statistically significant at the 0.01 probability level). Fe-DTPA was almost as closely related to total Fe uptake with a cor ela- tion coefficient of r equals 0.87 (statistically significant at the 0.01 probability level). DTPA-extractable soil Fe is typically closely associated with yields on soils low in plant-available iron.

Experiment 4

Soil. The comparative soils samples from the adjacent fields had higher levels of DTPA-extractable zinc in the surface 0-30 cm depths in the effluent-irrigated profile, with little difference in values at lower depths. Amount of DTPA-extractable manganese was less throughout

Table 8. Dry sorghum yields, iron plant tissue concentration and uptake and DTPA-extractable iron after iron chelate and RDSS treatments application, short-term application.

Treatments	Dry Yields[a] g/pot	Fe-Conc.[a] µg/gr	Fe-Uptake[a] µg/pot	Fe-DTPA[a] ppm
Soil only	0.74g	66.82a	49.45d	4.57e
RDSS 10 metric ton/ha	2.90d	29.46a	84.91d	7.99d
RDSS 20 metric ton/ha	4.38c	30.58a	131.66c	12.32c
RDSS 30 metric ton/ha	6.28b	31.02a	194.26b	16.16b
RDSS 40 metric ton/ha	7.54a	36.19a	271.08a	19.99a
F*	1.16efg	30.33a	35.18d	4.40e
S-138 Fe 10 kg/ha + F	1.36efg	33.87a	46.06d	4.43e
S-138 Fe 20 kg/ha + F	1.85e	26.19a	48.45d	4.72e
S-138 Fe 30 kg/ha + F	1.74ef	35.84a	62.36d	4.91e
S-138 Fe 5 kg/ha Fe-Active + F	3.41d	33.77a	116.82cd	5.36e
S-138 Fe 10 kg/ha	0.93fg	33.86a	31.49d	4.55e
S-138 Fe 20 kg/ha	1.33efg	38.60a	51.34d	4.59e
S-138 Fe 30 kg/ha	1.76ef	27.57a	48.52d	4.67e
S-138 Fe 5 kg/ha Fe-Active	3.46d	34.48	118.77cd	5.03e

[a]Means followed by the same letter are not significantly different at 5% level by Duncan's Multiple Range Test.

*F equals N-P_2O_5-K_2O (250-50-0) kg/ha: S-138 Fe equals Sequestrene - 138 Fe (6%).

the effluent-irrigated profile. DTPA-extractable iron levels were greater throughout the effluent-irrigated profile and more than three-fold greater at the surface. DTPA-extractable Zn, Mn and Fe values were all above published critical levels (49) and well within the range not to expect phytotoxicity problems.

Percent organic carbon tended to be higher in the first three depths in the profile irrigated with effluent and then differences tended to be none or small at lower depths. NO_3-N was greater throughout the profile using well water and CEC equivalent tended to be greater throughout the profile irrigated with effluent. No detrimental effects from the use of effluent are indicated by the organic carbon, NO_3 and CEC equivalent chemical properties. The trends indicated, i.e., higher organic carbon, lower NO_3-N and higher CEC, should be considered favorable effects, but it is difficult to apply economic benefits to these changes.

Plant Material. Corn and wheat crops growing at the sites irrigated with well water and with secondary sewage effluent for forty years did not show any visual phytotoxicity symptoms. They showed uniform and normal development, deep green color and were healthy-looking plants.

Chromium, Cd, Ni and Pb were not detectable in plant tissue digests at the <0.25 ppm detection level. Concentrations of Fe, Zn and Cu metals in corn leaf were significantly higher and Mn lower at the site irrigated with secondary sewage effluent. For corn stem tissues, no significant differences were noted for Fe and Cu levels, but Zn concentrations were significantly higher and Mn significantly lower at the site irrigated with effluent compared to ground water. In wheat tissue, iron was the only metal whose concentrations were significantly higher at the site irrigated with secondary sewage effluent. Concentrations of all elements in plant tissue were well below the tolerance levels of metals for agronomic crops suggested by Melsted (43).

Concentrations of nutrients and heavy metals analyzed for in Zea maize grain and cob plus sorghum are given in Table 9. Levels of nutrients and metals are within ranges considered normal for these grains.

SUMMARY AND CONCLUSIONS

Information has been given indicating that the "radiation" process of reducing pathogens in sewage products being developed by Sandia Laboratories, Albuquerque, New Mexico, does not significantly increase the chemical extractability and plant uptake of a broad range of nutrients and heavy metals. Therefore, results of experiments on using sludges on calcareous soils should not differ greatly whether the sewage products are radiation treated or untreated.

However, radiation treatment greatly facilitates handling sewage for experimentation, because pathogen contamination precautions are eliminated and weed seeds killed. Rosopulo _et al_. (53) studied the effects of sludge irradiation on plant nutrient uptake and found no concentration increases agreeing with results presented herein.

Table 9. Concentrations of mineral elements and heavy metals in specimens of crops from a site near Clovis, New Mexico, having 40-year history of irrigation with sewage effluent or local groundwater.

Specimen/Treatment	Content of Element in Plant Dry Matter									
	Ca	P	Zn	Fe	Mn	Cu	Ag	Ni	Cr	Cd
	%	%	ppm							
Maize Grain										
Sewage effluent	.012	.298	56.8	31.5	6.7	<.02	<.01	<.02	<.02	<.004
Ground water	.013	.367	43.0	25.4	8.2	<.02	<.01	<.02	<.02	<.004
	NS	**	NS	*	**	NS	NS	NS	NS	NS
Corncobs										
Sewage effluent	.018	.040	32.2	101	4.7	<.02	<.01	<.02	<.02	<.004
Groundwater	.023	.101	25.4	167	11.2	<.02	<.01	<.02	<.02	<.004
	NS	**	NS	**	**	NS	NS	NS	NS	NS
Sorghum Grain										
Sewage effluent	.095	.335	35.0	98.0	27.5	<.02	<.01	<.02	<.02	<.004
Groundwater	.004	.282	95.7	56.0	14.7	<.02	<.01	<.02	<.02	<.004
	NS	NS	NS	NS	**	NS	NS	NS	NS	NS

NS Indicates that values for means are not significantly different, $P > .05$.

*Means are different, $P < .05$

**Means are different, $P < .01$

Experimentation published to date is sufficient to forego recommending indiscriminate use of sewage sludge on all agricultural land, CAST (12). However, sewage products may have special potential for use on calcareous soils, such as in the State of New Mexico in the southwestern United States. For instance, in New Mexico the lack of potassium in sewage products is not a problem because most New Mexico soils contain sufficient K for good crop growth and K is not routinely added as a fertilizer. The naturally high pH (pH 7.5 to 8.0 or higher) of New Mexico soil greatly reduces plant availability of many problem heavy metals.

Dramatic increases in yield over and above that expected for N, P inputs from sewage are typified by the greenhouse and field results presented herein, especially for the known micronutrient deficient soils of New Mexico. Results idnicate that sewage sludge is apparently an excellent Zn and Fe fertilizer. However, more research needs to be done before the economics of sludge application can be calculated and more field information is needed on applications of dry irradiated sewage solids on various crops and soils before irradiated sewage products are used indiscriminately.

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