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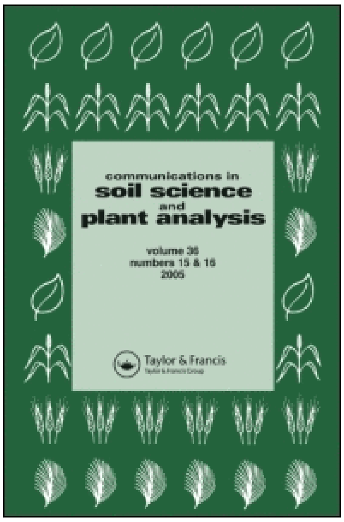

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Potential of Gamma Irradiated Sewage Sludge as Fertilizer in Radish: Evaluating Heavy-Metal Accumulation in Sandy Loam Soil

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*Soil application of sewage sludge as an amendment in crop plants has became a popular method of municipal sewage-sludge disposal in many countries. However, the presence of heavy metals in untreated sewage sludge has raised concerns of adverse effects on crop growth, quality of product, and environmental health. Gamma irradiation is one of the treatments for hygienization of sewage sludge before use as fertilizer. To evaluate the potential of gamma-irradiated sewage sludge as fertilizer in vegetable crops, the field investigation was conducted in a root crop, radish (*Raphanus sativus *L.), during the 2005–06 and 2006–07 growing seasons in a sandy loam soil. Treatments consisted of three source of fertilizers [farmyard manure (FYM), gamma-irradiated sewage sludge (GISS), and nonirradiated sewage sludge (NISS)]; each were compared at six application levels (1, 3, 6, 7, 9, and 11 t ha^{-1}). The physicochemical properties of all the three fertilizers used in this study were compared. Growth parameters and yields of radish were not significantly influenced by source of fertilizers or their application levels, except plant stand, which was influenced by type of fertilizers used. There was no significant difference observed between source of fertilizer treatments with respect to any of the measured soil properties, including major nutrients [nitrogen (N), phosphorus (P), and potassium (K)], metallic micronutrients [copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)], and heavy metals [nickel (Ni), lead (Pb), cadmium (Cd), and cobalt (Co)]. Soil P and Zn were influenced by the various level of fertilizers. However, the interaction effect of source and level of fertilizer was absent for all the measured parameters. The maximum pollutant limits in sewage sludge and soil for agricultural use in different countries were compared. The concentration of metallic micronutrients and heavy metals in soil were less than the prescribed limit of the United States Environmental Protection Agency (USEPA), and no significant accumulation was noted after 2 years of application of GISS and NISS even at higher application rates.*

Keywords Farmyard manure, fertilizer, gamma irradiation, heavy metals, hygienization, irradiated sludge, sewage sludge

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Introduction

As a result of large-scale urbanization and industrial development, the generation of sewage sludge has increased rapidly during the past few decades (Rathod et al. 2008; WWAP 2003). Governments throughout the world are facing a problem of management and disposal of a large quantity of sewage sludge (Mor et al. 2006a; USEPA 1993). High cost of land filling of sewage sludge and a ban on ocean dumping in a few countries are some factors that contribute to recycling of sewage sludge (Harrison, McBride, and Bouldin 1999; Rathod et al. 2008). Sewage sludge is a cheap source of appreciable amounts of plant nutrients and organic matter (Gautam et al. 2005). On an average, sewage sludge contains about 3.2% nitrogen (N), 2.3% phosphorus (P), and 0.3% potassium (K); and therefore during the past two decades, the use of sewage sludge as fertilizer increased in many countries (Hornick et al. 1984; Krogman et al. 1997). However, the direct use of sewage sludge has a few environmental and public health concerns (Dewil, Baeyens, and Neyens 2006) because of the presence of heavy metals, pathogenic bacteria, and other toxic substances that may limit its application as soil fertilizer (Wen et al. 1995; Rathod et al. 2008). Another concern is groundwater contamination because of heavy-metal infiltration by precipitation from soil-applied sewage sludge (Mor et al. 2006b).

Recognized processes for sewage-sludge treatments are gravity thickening, chemical conditioning, aerobic digestion, and anaerobic digestion followed by final disposal, composting, land application, landfill, and so on have been adopted (Krogman et al. 1997). However, heavy metals in sewage sludge could not be eliminated by common sludge treatment methods such as aerobic or anaerobic digestions (Dewil, Baeyens, and Neyens 2006). Thus, there exists a need to further extend the treatment process to include a step that ensures removal of the pathogenic bacteria with a high degree of reliability. Some advanced treatment processes including acid and alkaline thermal hydrolysis and peroxidation were confirmed, which have the potential to enhance the dewaterability of the sludge by degrading the extracellular polymeric substance structures (Neyens and Baeyens 2003a, 2003b).

In the search for an alternative method to treat and/or disinfect sewage sludge, ionizing radiation (to convert nonbiodegradable substances to more readily degradable substances and to eliminate microorganisms) was successfully implemented for large-scale treatment of sewage sludge (Lessel 1988; Getoff 1992). Irradiation facilities for treatment of sewage sludge have been adopted in many countries. India's Sludge Hygienization Research Irradiator (SHRI) is the second plant in the world built in 1992 as a collaborative program between Bhabha Atomic Research Center (BARC), Mumbai, Vadodara City Municipal Corporation, and the government of Gujarat, India. The main objective was to treat sewage-sludge output of about 110 m^3 day^{-1} and use the hygienized sludge as safe fertilizer on agricultural farm land (Swinwood et al. 1994).

Ionizing radiation is recognized as an efficient and rapid method of sewage-sludge treatment (Bauer 1994; Getoff 1992, 1996; Waite et al. 1992). Several studies have confirmed the efficacy of ionizing radiation for treating sewage sludge (Lowe et al. 1956; Pikav and Shubin 1984; Hashimoto et al. 1986; Lessel 1988; Swinwood and Fraser 1993; Wang and Wang 2007). Among many types of radiation (viz., gamma, beta, alpha, x-ray, and ultraviolet), gamma radiation is the most commonly used in the treatment of sewage sludge (Getoff 1996). Effective hygienization of sewage sludge by gamma radiation is well documented (Kapila et al. 1981; Pandya, Prakash, and Modi 1988; Rawat, Sharma, and Rao 1998). Radiation dosages of gamma radiation vary from 2 to 25 kGy (Pandya, Prakash, and Modi 1988).

Gamma irradiator (^{60}Co) has been widely used since the early 1960s in the sterilization of medical products and consumer goods. The previous studies on application of radiation technology to wastewater treatment were started as early as in the 1950s (Borrely et al. 1998). However, little attention has been paid to this emerging technology until recent years, and it has not yet been commercially accepted and documented (Jung, Thornton, and Chon 2002; Pikav and Shubin 1984). Many countries including Germany, India, Italy, and the USA have successfully adopted the use of irradiation technology to disinfect sewage sludge prior to application on agricultural farmlands (Swinwood et al. 1994). In the USA, approximately 6.9 million Mg of sewage sludge were generated in 1998, and among them 60% were used either through land application, composting, or as landfill cover. This number is expected to increase to 8.2 million Mg in 2010. In India, only 30% of the sewage sludge is being treated before its discharge (GOI 2002). Total sewage generation from urban regions in India is about 30 billion L a day, while the total sludge treatment capacity is estimated to be only 3 billion L a day (GOI 2002).

When sludge is subjected to ionizing radiation, the following events can be observed: (i) oxidation of organic molecules, (ii) disturbance of the structure of organic and inorganic molecules, (iii) changes in colloidal systems, followed by (iv) killing of microorganisms (Borrely et al. 1998). The rationale for utilizing radiation in treatment of sewage sludge rests on a number of documented facts. Many practical advantages of gamma-irradiated sewage sludge (GISS) have been documented (Rathod et al. 2008). On the other hand, if municipal sewage sludge is disposed of untreated, it may result in public health hazards as it contains a high load of heavy metals, pathogenic bacteria, and viruses (Pike 1986; Ahmed and Sorensen 1997), in addition to useful major and micronutrients (Jung, Thornton, and Chon 2002). The legal restrictions concerning the heavy-metal content in sewage sludge for use in agriculture as a fertilizer have been imposed in many countries (Table 1). For example, in the European Union, the maximum acceptable concentrations of heavy metals in sewage sludge are explained in Directive 86/278/EEC of the European Commission (Commission of the European Communities 1986) and in the USA by U.S. EPA Part 503 regulations based on the risk assessment studies (USEPA 1993). However, the maximum pollutant limits in sewage sludge for use in agriculture and soil vary from country to county (Tables 1 and 2).

Gamma-irradiated sludge is qualitatively different from the sludge obtained with conventional treatment methods (Pikav and Shubin 1984). Untreated sewage sludge applied to

Table 1
Comparison of maximum pollutant limits (mg kg^{-1}) in sewage sludge for agricultural use in different countries

Pollutant	USEPA[a]	EU[b]	Denmark[c]	Belgium[b]
As	41	—	25	—
Cd	39	20–40	0.8	3.6
Cu	1500	1000–1750	1000	277
Pb	300	750–1200	120	172
Hg	17	16–25	0.8	1.93
Ni	420	300–400	30	52
Se	100	—	—	—
Zn	2800	2500–4000	4000	1222

[a] Harrison et al. (1999).
[b] Dewil et al. (2006).
[c] Danish Ministry (1996).

Table 2
Comparaisons of maximum pollutant limits (mg kg^{-1}) in soil in different countries

Pollutant	USEPA[a]	Canada[b]	India[c]	Romania[d]
As	0.4	14	—	—
Cd	0.4	1.6	3–6	1–3
Cu	—	100	135–270	12
Pb	400	60	250–500	50–300
Hg	—	0.5	—	1–5
Ni	7	32	75–150	30–75
Se	0.3	1.6	—	—
Zn	620	220	300–600	150–300

[a] Harrison et al. (1999).
[b] OMEE (1996).
[c] Awashthi (2000).
[d] Ailincai et al. (2007).

agricultural land may pollute the ecosystem, if the pollutants are high and accumulate in the soil. Hence, an attempt was made to evaluate the effect of GISS on the yields of crop and physicochemical properties of soil. The study also includes assessment of the quality of the fertilizers with respect to the concentration of major nutrients, metallic micronutrients, and heavy metals in soil and crop applied under the natural field conditions.

The experiment was carried out to evaluate the superiority of the irradiated sludge (at different levels, if any) for its suitability as fertilizer with the specific objectives: (1) to characterize the GISS and nonirradiated sewage sludge (NISS) in terms of physical and chemical properties and toxic organic compounds; (2) to quantify the impact of GISS on crop yields and soil fertility, including major and micronutrient availability; and (3) to quantify the extent of contamination of sandy loam soil by sludge-derived heavy metals.

Materials and Methods

Experimental Site and Soil Type

The present study was conducted at the experimental farm, located at the Regional Research Station, Anand Agricultural University (AAU), in the state of Gujarat, India. The experimental field was cropped with a root crop, radish, for two consecutive years (2005–06 and 2006–07). The field plots received the same treatments during both years. The same experimental plots were utilized for both years. The soil of the experimental site was alluvial in nature, locally known as *Goradu*, with texture ranging from loamy sand to sandy loam (Typic Ustocrepts). The soil was low in nitrogen (N) and medium in phosphorus (P) and potassium (K). The climatic zone represents the semi-arid and subtropics with hot summer and cool winter.

Irradiation of Sewage Sludge

The GISS and NISS were transported to the experimental site at the experimental farm, AAU, Anand, located 50 km away from SHRI, Vadodara. The farmyard manure (FYM) used in this study was purchased from a local dealer in Anand. The heavy-metal contents in GISS and NISS were less than the maximum permitted limit established by the U.S. EPA (USEPA, 1993).

Field Experimentation and Sewage-Sludge Treatment

Field experiment was carried out during the *rabi* (winter: October to February) season of 2005–06 and 2006–07 at the Regional Research Station, Anand Agricultural University, Anand, Gujarat. Radish (*Raphanus sativus* L.), a member of the family Brassicaceae, is a cool-season, fast-maturing vegetable crop. The seed of radish crop was purchased from the local market in Anand.

A week before sowing the crop in October 2005 and 2006, irradiated and nonirradiated sewage sludge (as per the treatment doses on respective randomized plots) were broadcast and incorporated into the soil at 10- to 15-cm depths followed by light irrigation to ensure prior decomposition of added sewage sludge. Radish seed was broadcasted at the seeding rate of 10 kg ha^{-1} evenly followed by light irrigation. The size of each plot was 4.0×1.8 m. Treatments were laid out in a three by six factorial randomized complete block design (FRBD). Each block had 18 treatments, and each treatment was replicated three times. Treatments consisted of three sources of fertilizers (S_1: FYM; S_2: GISS; and S_3: NISS), each at six different levels of application (L_1: 1 t ha^{-1}, L_2: 3 t ha^{-1}, L_3: 6 t ha^{-1}, L_4: 7 t ha^{-1}, L_5: 9 t ha^{-1}, and L_6: 11 t ha^{-1}). Irrigation was applied by surface irrigation channel as and when required during the crop season.

Soil Sampling

Soil samples were collected by using the pipe auger method at the depth of 0–15 cm from three spots selected randomly from each net plot area after harvesting of the crop. Soil samples were dried, crushed to pass through a 2-mm mesh sieve, and then preserved for chemical analysis. Growth parameters such as plant stand (number of plants) per net plot area and girth and length of radish root were also recorded as an average of three plants selected from the net plot area.

Chemical Analysis of Sludge and Soil

The pH and organic matter (OM) of sewage sludge were determined using standard analytical methods (Jackson 1973). Organic N in sewage sludge was analyzed by Kjeldahl's method. Phosphorus, K, micronutrient [zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu)] and heavy metal [nickel (Ni), lead (Pb), cadmium (Cd), and cobalt (Co)] contents of sewage sludge were determined by using a digestion system with the following method: 0.5 g sludge dry weight (DW) + 10 mL diacid mixture [nitric acid (HNO_3) + perchloric acid ($HClO_4$) in 2:1 ratio] digested at the temperature of 140 °C for 6–8 h. The digested solution was analyzed for P by Olsen's method, K by spectrophotometry (Jackson 1973), and metallic micronutrients and heavy metals using atomic absorption spectroscopy (AAS; Chemito AA203, Chemito Instruments, Mumbai, India).

The pH and electrical conductivity (EC) of soil samples were measured from soil/water (1:2.5 w/v) suspension. Soil-available P was extracted with sodium bicarbonate ($NaHCO_3$) and measured as described by Olsen and Sommers (1982). Available K was extracted using 1 *M* neutral ammonium acetate (CH_3COONH_4) and measured with flame photometry (Jackson 1973). Other soil chemical properties were analyzed using standard methods: organic C by Walkley and Black method; organic N by Kjelhdahl's method; micronutrients (Cu, Fe, Mn, and Zn) and heavy metals (Ni, Pb, Cd, and Co) by diethylenetriaminepentaacetic acid (DTPA) extraction subject to AAS as mentioned in Jackson (1973).

Statistical Analysis

An analysis of variance (ANOVA) was performed on the untransformed data from each growth season (2005–06 and 2006–07). The pooled data from both the years were also calculated to test for differences among treatments at the 5% level of significance ($P < 0.05$). The statistical analysis package (SPSS) for the factorial randomized complete block design was used (Chandel 1970). Each value represents the mean of at least three plants and soil samples from each net plot for both the years. The significance and nonsignificance of a given variance was determined by calculating the standard error (SE) and CD values. CD is the Critical Difference between the Treatments. Significance of difference between two means can be tested by the statistic CD value. CD = SEd × t table value at 5 % (at error degree freedom), where SEd is Standard Error of Difference. The coefficient of variation (CV%) was also calculated via standard formula (Chandel 1970).

Results and Discussion

Chemical Analysis of Soil and Fertilizers

The experimental soil was sandy loam with a pH value of more than 8.0 (Table 3). The analysis of major nutrients of soil (N, P, and K) before fertilizer treatments suggests that soil was low in N, medium in P, and moderate in K. The values of N, P, and K were slightly

Table 3
Soil physicochemical characteristics of the experimental site before fertilizer treatments

Characteristics	2005–06	2006–07
Texture	Sandy loam	Sandy loam
pH (1:2.5)	8.03	8.07
EC (1:2.5) dS m^{-1}	0.13	0.11
Total nitrogen (kg ha^{-1})	1258	1270
Available P_2O_5 (kg ha^{-1})	43.50	50.20
Available K_2O (kg ha^{-1})	275	281
Organic carbon (%)	0.33	0.39
DTPA Zn (mg kg^{-1})	1.15	1.18
DTPA Mn (mg kg^{-1})	11.50	11.89
DTPA Fe (mg kg^{-1})	10.00	12.70
DTPA Cu (mg kg^{-1})	1.25	1.30
DTPA Ni (mg kg^{-1})	0.13	0.16
DTPA Pb (mg kg^{-1})	0.47	0.51
DTPA Cd (mg kg^{-1})	0.11	0.13
DTPA Co (mg kg^{-1})	0.32	0.37

greater in the second year of the field experiment (2006–07). This may be because of the addition of the fertilizers in the first growing season (Table 3). A similar trend was observed in metallic micronutrients (Zn, Mn, Fe, and Cu) and heavy metals (Ni, Pb, Cd, and Co). However, the concentrations of heavy metals were far less than the U.S. EPA and Indian threshold levels (Table 2).

Before attempting to assess the utilization of sewage sludge as fertilizer in agronomic and horticultural crops, the physical and chemical properties of the sewage sludge were characterized (Epstein, Taylor, and Chaney 1976). The physicochemical characteristics of all three fertilizers used in this experiment were determined and compared (Table 4). All three fertilizers had a pH less than neutral, high organic matter, and high bioavailable elements. Particularly at greater rates, the sludge application may increase the availability of micronutrients. The GISS and NISS were almost equal in N and P content in comparison to FYM. However, FYM was rich in K (Table 4). Thus, the macronutrients (especially N and P) may serve as a good source of plant nutrients supplied by application of sewage sludge.

Most of the physicochemical parameters of sludge remain unaltered after exposure to gamma radiation, except for some micronutrients and heavy metals. For example, Zn and Mn were greater in GISS than in NISS. A similar difference was noticed for Cu and Pb (Table 4). This might be because gamma irradiation of sewage sludge may result in increase mobility of metals, probably because of an increase in more easily adsorbed free forms of metals derived from the degradation of soluble organic complexes (Campanella et al. 1989). This also indicates that gamma irradiation increased metal availability more than overall solubility. It might be because of ability of these metals (Cu and Pb) to modify the molecular structure of the heterogeneous polymers present in the sewage sludge by attacking unsaturated bonds and degrading aromatic structures (Stevenson 1982).

Similar results have been reported by Rawat, Sharma, and Rao (1998), Kirkham (1980), and El Motaium and Badawy (2002). Wen, Voroney, and Winter (1997) also stated

Table 4

Physicochemical characteristics of the fertilizers used in this experiment

	FYM			
Characteristics	2005−06	2006−07	GISS[a]	NISS[b]
pH (1:2.5)	6.44	6.50	6.60	6.64
Nitrogen (%)	1.40	1.46	1.77	2.00
P_2O_5 (%)	0.40	0.50	0.20	0.23
K_2O (%)	0.25	0.34	0.17	0.18
OM (%)	31.20	35.60	36.70	42.57
Zn (mg kg^{-1})	105.0	112.50	441.00	49.08
Mn (mg kg^{-1})	160.5	173.40	334.50	25.53
Fe (mg kg^{-1})	2934	3250	6654	6807.00
Cu (mg kg^{-1})	139.0	142.00	159.00	2.19
Ni (mg kg^{-1})	7.1	8.1	9.4	12.23
Pb (mg kg^{-1})	9.01	10.21	8.29	1.45
Cd (mg kg^{-1})	1.88	2.12	1.13	14.00
Co (mg kg^{-1})	4.00	4.07	6.89	6.40

[a] GISS, gamma-irradiated sewage sludge.

[b] NISS, nonirradiated sewage sludge.

that irradiation of sludge did not significantly affect sludge organic C or N mineralization. In contrast to this, McCaslin and O'Connor (1982) revealed that the radiation process of reducing sewage sludge pathogens did not significantly increase the chemical extractability of nutrients or heavy metals. The high organic-matter contents of GISS (36.70%) and NISS (42.57%) may improve the soil physical properties significantly (Table 4). Analysis of the chemical composition of sewage sludge collected from different cities in Indiana showed that it contained approximately 50% organic matter (Sommers 1977).

The greater concentration of heavy metals in sewage sludge in comparison to FYM was because the raw material of sewage sludge was from municipality waste, household wastewater, and other industrial wastes. The concentration of Cd in all the fertilizers was much less than the maximum limit of 39 mg kg^{-1} established by the U.S. EPA (Harrison, McBride, and Bouldin 1999). Likewise, Pb, Zn, Cu, and Ni concentrations in all three fertilizers were less than U.S. EPA permissible limits of 300, 2800, 1500 and 420 mg kg^{-1}, respectively (Tables 1 and 4). The FYM used in this study was of exceptionally good quality with 1.40–1.46% N. Comparatively more N was observed in GISS (1.77%) and NISS (2%), but it was vice versa with P and K contents (Table 4).

Many researchers have stated that application of sewage sludge to soil should only be allowed after their chemical, physical, and nutritional characterization (Harrison, McBride, and Bouldin 1999; Gautam et al. 2005). The physicochemical properties of sludge may vary depending on the origin of sewage sludge, the treatment of sludge, the rate at which it is applied to soil, type of crop grown, and use of other fertilizers. The results of chemical analysis of fertilizers revealed that recycling of sewage sludge may be possible, if it has no any adverse effect on soil and plant properties. The gamma irradiation has resulted in greater amount of certain micronutrients (Zn, Mn) and heavy metals (Cu, Pb) in sludge in comparison to NISS (Table 4). Thus, the analysis of the soil chemical properties for heavy-metal accumulation after treated and untreated sludge application is required to understand the impact of irradiation on soil properties. Since the average organic matter of soil in India is low, the potential source of sewage sludge can be of great help to farmers in maintaining soil organic matter and nutrients. Such recycling will also prevent pollution resulting from accumulation of sludge at one place.

Effect on Crop Yield and Growth Parameters

Effect of Source of Fertilizers. The yield of the radish crop and plant growth parameters (plant stand, root length, and root girth) were not statistically influenced by the source of fertilizers (S_1, S_2, and S_3) in any growing season and also in pooled data, except for the plant stand (Table 5). The greatest number of plants plot^{-1} was recorded in the S_2 treatment, but it was statistically at par with NISS and FYM treatments. Maximum yield (60.73 q ha^{-1}) was obtained in the second year of study with NISS application, but statistically it was at par with the other two treatments (Table 5). More yields were obtained during the second year of experiment (2006–07) in comparison to the first year (2005–06), which may be because the application of the fertilizer in the first year supplied mineral nutrients and organic matter to the soil. It was also reflected in the chemical analysis of the soil in the second year before fertilizer treatment, as mentioned in Table 4.

Many researchers have shown that the addition of sewage sludge increases the growth and production of several agronomic and horticultural crops (Pandya, Prakash, and Modi 1988; Pandya, Sachidanand, and Modi 1989; Hornick et al. 1984). About 30% greater yield of fescue under the application of sewage sludge was noticed (Boswell 1975). Antolin et al. (2005) evaluated the effect of sewage sludge on barley yield and suggest that grain yield of

Table 5

Influence of various sources and levels of fertilizers on yield and growth parameters of radish

	Yield (q ha^{-1})			Plant stand (no. plot^{-1})			Root length (cm)			Root girth (cm)		
Treatment	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled
Source of fertilizers (S)												
S_1	46.29	55.43	50.86	228.11	229.78	228.94	23.61	23.97	23.79	11.09	11.09	11.09
S_2	48.55	57.22	52.89	264.39	266.06	265.22	24.69	25.53	25.11	11.21	11.21	11.21
S_3	49.34	60.73	55.03	254.33	256.00	255.17	23.58	23.94	23.76	10.86	10.86	10.86
SE (±)	0.92	2.59	1.94	13.82	13.82	13.82	0.68	0.70	0.69	0.20	0.20	0.20
CD @ 5%	NS	NS	NS	NS	NS	39.00	NS	NS	NS	NS	NS	NS
Level of fertilizers (L)												
L_1	47.55	63.67	55.61	245.11	246.78	245.94	22.56	23.21	22.88	10.50	10.71	10.60
L_2	50.99	56.02	53.50	260.33	262.00	261.17	23.89	24.25	24.07	11.22	11.19	11.20
L_3	44.53	54.78	49.66	244.22	245.89	245.06	24.11	25.10	24.60	10.94	11.01	10.98
L_4	51.85	60.00	55.93	246.22	247.89	247.06	23.56	23.91	23.73	11.17	11.39	11.28
L_5	47.38	56.70	52.04	266.67	268.33	267.50	24.33	24.70	24.52	10.78	10.99	10.89
L_6	46.07	55.59	50.83	231.11	232.78	231.94	25.33	25.72	25.52	11.33	11.40	11.37
SE (±)	1.30	3.66	1.37	19.55	19.55	9.77	0.96	0.99	0.49	0.28	0.28	0.14
CD @ 5%	3.74	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S × L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	8.13	18.98	15.56	23.55	23.40	23.48	12.01	12.11	12.06	7.59	7.43	7.51

barley increased significantly under repeated sludge application. Thus, the results of radish yield and growth parameters influenced by type of fertilizers used in this study revealed that land application of sewage sludge has a great incentive in view of its fertilizer and soil-conditioning properties and it can be an alternative to FYM, without crop yield penalty.

Effect of Level of Fertilizers. The crop yield was significantly affected by the various levels of fertilizers in the first year of study (2005–06). However, in the second year and in pooled analysis, the effect was nonsignificant (Table 5). During the first year, maximum yield (51.85 q ha^{-1}) was recorded when the fertilizer was applied at the rate of 7 t ha^{-1} (L_4) but it was statistically near to the lower level of 3 t ha^{-1} (L_2, 50.99 q ha^{-1}). In an experiment on the various levels of sewage sludge in maize, Ailincai et al. (2007) suggest that sewage sludge applied at the rate of 40 t ha^{-1} resulted in an increased amount of minerals, especially N and P, but when raw sewage sludge was applied at the rate of 60 t ha^{-1}, the limits were exceeded for Zn content. About 30% greater yield of fescue (*Festuca arundinaceous* Schreb.) was noticed under excessive application of sewage sludge, when applied three times over a 2-year period compared to control (Boswell 1975). To determine the various levels of raw sewage-sludge compost on the yield of maize, amaranthus, cowpea, and crossandra under controlled conditions, Chitdeshwari, Savithi, and Mahimairaja (2002) concluded that the sewage-sludge compost enhanced the yield of all the plants compared to the unamended control and the yield of crops increased with increasing the level of fertilizers.

Interaction Effect. Interaction effect of type and level of fertilizers had a nonsignificant effect on the crop yield. This result was in agreement with Athalye et al. (1999) and Fauziah and Rosenani (1999). They also reported the same trend for maize-green gram and corn (*Zea mays*) yields with application of irradiated and nonirradiated sewage sludge. Contrary to the present results, with application of irradiated sludge, El Motaium and Badawy (2002) and Pandya, Banerjee, and Modi (1991) obtained greater yield in tomato (*Lycopersicon esculentum* L.) and methi (*Trigonella foenum-graecum* L.), respectively. Zhou et al. (1999) also reported that rice and wheat yields were greater in soil receiving greater rates of irradiated sludge. The presented results suggest that the sewage sludges (both GISS and NISS) were as good as the conventional source of manure (FYM) for radish crop. Magnavacca (1999) and Pandya et al. (1988, 1889, 1991) studied the impact of gamma-irradiated sludge in sugarcane, rice (*Oriza sativa*), chickpea (*Cicer arietinum*), and methi (*Trigonella foenum-graecum* L.) and revealed that it could have beneficial use for agricultural crops.

Results of growth parameters (plant stand, radish root length, and girth) also did not differ significantly as a result of interaction effect of type and level of fertilizers used (Table 5). No phytotoxic symptom was observed on radish plants in any treatment, which suggests that there was no negative interaction impact of source and level of fertilizers. Pandya, Sachidanand, and Modi (1989) revealed that the retarding effect of nonirradiated sludge on chickpea (*Cicer arietum*) root length, fresh weight, and dry weight was nullified with gamma-irradiated sludge treatment.

Effect on Soil Organic Carbon, pH, and EC

The impact of fertilizers on soil organic C, pH, and EC were studied, and the data are presented in Table 6. Soil organic C, pH, and total salts (EC) also did not vary significantly due to source or level of fertilizers used (Table 6). In another study, when GISS was applied

Table 6

Influence of various sources and levels of fertilizers on soil organic carbon, pH, and EC

	Organic carbon (%)			pH (1:2.5)			EC (dS m^{-1})		
Treatment	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled
Source of fertilizer (S)									
S_1	0.36	0.36	0.36	7.96	7.98	7.97	0.116	0.120	0.118
S_2	0.35	0.36	0.35	7.95	7.97	7.96	0.123	0.129	0.126
S_3	0.37	0.38	0.37	7.95	7.97	7.96	0.118	0.124	0.121
SE (±)	0.01	0.01	0.01	0.05	0.05	0.05	0.004	0.005	0.004
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of fertilizer (L)									
L_1	0.34	0.34	0.34	8.00	8.02	8.01	0.122	0.127	0.125
L_2	0.37	0.38	0.38	7.92	7.93	7.93	0.124	0.129	0.127
L_3	0.34	0.35	0.34	7.95	7.97	7.96	0.111	0.116	0.113
L_4	0.37	0.38	0.38	7.95	7.96	7.96	0.122	0.124	0.123
L_5	0.37	0.38	0.37	7.94	7.96	7.95	0.123	0.131	0.127
L_6	0.36	0.37	0.37	7.97	7.99	7.98	0.110	0.119	0.115
SE (±)	0.02	0.02	0.01	0.06	0.06	0.03	0.005	0.006	0.003
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
S × L	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	14.13	14.09	14.11	2.45	2.44	2.45	13.51	15.36	14.51

in the range of 6–24 t ha^{-1} in a vegetable crop chili (*Capsicum annuum* L.), soil organic matter and the yield consistently increased (Mitrosuhardjo et al. 1999). Many factors that may influence metal solubility and movement in sludge-amended soil include total metal concentration, organic matter, pH, and texture (Welch and Lund 1987). The other factors include concentration of organic/inorganic agents and cations; soil binding sites have also been indicated to affect metal mobility (Tyler and McBride 1982).

In view of the heavy-metal abundance in sludge, soil pH consideration is important. The data on effect of sewage-sludge application on soil pH is not consistent. Soil pH increases have been reported in soils treated with sludge (Tsadilas et al. 1995). On the other hand, lowering of soil pH is also reported (Epstein, Taylor, and Chaney 1976). In this study, soil pH was slightly reduced by application of all three fertilizers (Table 6). The decrease in soil pH may be due to microbial activity and organic acid production during the degradation of sewage sludge. The decrease in pH also affects the metal mobility, as most of the metals are more soluble at lower pH values. The calcium carbonate content of sludge and acid decomposition after sludge decomposition are two factors correlated with changes in soil pH (Sommers 1977). Antolin et al. (2005) also concluded that the repeated sludge application reduced the soil pH and increased the total organic C and cation exchange capacity.

Effect on Major Nutrients of Soil

It is evident that none of the analyzed soil properties was significantly influenced by application of GISS in comparison to NISS and FYM, except P (Table 7). There were no major differences in N and K contents of soil that received GISS, NISS, or FYM (Table 7). The availability of N and P is the key for crop growth. Among the different application levels of fertilizers, significantly greater soil P (85.69 kg ha^{-1}) was observed in the second growing season (2006–07) and also in the pooled data, when the fertilizer was applied at the rate of 5 t ha^{-1} (Table 7). This might be because almost all major sources of organic wastes such as sewage sludge and livestock manure often contain plenty of P (USEPA 1993; OMAF 1990). The high value of pH (8.03–8.07) of the experimental site (Table 1) generally causes P precipitation as calcium phosphates, which might be favored at high temperatures. Magnavacca (1999) evaluated the potential of irradiated sewage sludge as fertilizers in ryegrass and sugarcane and showed that irradiated sludge was a good source of N and P.

The interaction effect of source and level of fertilizers was nonsignificant also for P (Table 7). Soil N and K contents were not influenced by fertilizer application rates, even at greater doses, and thus this fact should be considered when recommending sewage sludge for nutrient supply for radish crop in sandy loam soil. In contrast to our results, Athalye et al. (1999) reported that irradiated sewage sludge significantly increased the organic N in soil at all the rates of application (1–8 t ha^{-1}), while no variation in P and K contents as a result of either irradiated or nonirradiated sludge at any application rate was observed.

Soils in cultivated fields in western central India (Gujarat) is poor in organic matter and some nutrients. Organomineral resources such as sewage sludge could be an acceptable substitute for expensive commercially produced fertilizers, and more important, it could contribute to the improvement of organic-matter content in the soil. The results show that the application of 6 t ha^{-1} sewage sludge increased the supply of mineral elements (especially P) without yield reduction. Because the sewage sludge is rich in organic matter (about 36–40%, Table 4), it also ensures a significant amount of annual supply of organic matter, which may increase the soil humus content. However, the conditions for continuous improvement of sewage sludge by hygienization treatment such as gamma irradiation must be met to avoid any negative consequences on soil health and environment.

Table 7
Influence of various sources and levels of fertilizers on major nutrients of soil

	Organic N (%)			Available P_2O_5 (kg ha^{-1})			Available K_2O (kg ha^{-1})		
Treatment	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled
Source of fertilizers (S)									
S_1	0.031	0.031	0.031	89.18	77.06	83.12	244.05	242.57	243.31
S_2	0.030	0.031	0.031	89.68	77.65	83.66	238.56	245.55	242.05
S_3	0.032	0.033	0.032	90.13	77.09	83.61	252.09	247.54	249.81
SE (±)	0.001	0.001	0.001	1.39	1.19	1.30	7.96	8.47	8.22
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of fertilizers (L)									
L_1	0.029	0.030	0.029	87.99	74.83	81.41	233.03	240.10	236.56
L_2	0.032	0.033	0.033	89.20	75.94	82.57	239.33	229.60	234.47
L_3	0.029	0.030	0.030	89.44	85.69	87.57	242.55	255.16	248.85
L_4	0.032	0.033	0.032	89.70	75.16	82.43	247.16	248.65	247.90
L_5	0.032	0.032	0.032	91.38	75.17	83.27	242.21	236.90	239.56
L_6	0.031	0.032	0.032	90.26	76.82	83.54	265.11	260.90	263.00
SE (±)	0.001	0.001	0.001	1.97	1.68	0.92	11.26	11.98	5.81
CD @ 5%	NS	NS	NS	NS	4.82	2.58	NS	NS	NS
S × L	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	14.16	14.12	14.14	6.60	6.52	6.58	13.79	14.65	14.23

Effect on Soil Micronutrients and Heavy Metals

The government authorities permit the application of sewage sludge to agricultural land with the assumption that the soil accumulations of heavy metals from sludge will not cause environmental or health hazard (USEPA 1993). However, the accumulation of heavy metals in soil has been cited as a potential hazard by many environmentalists (McBride et al. 1999). Data on DTPA-extractable micronutrients (Zn, Mn, Fe, Cu) and heavy metals (Ni, Pb, Cd, Co) in soil also followed a nonsignificant trend in both years, as well as in pooled analysis, which suggests that they were not influenced by type or level of fertilizers used or their interaction effect (Tables 8 and 9), except for Zn, where the various level of fertilizers affected the Zn concentration in soil (Table 8). The maximum concentration of Zn was recorded when the greatest rate of fertilizer (11 t ha^{-1}) was applied, and statistically it was at par with treatments L_3 and L_5 (Table 8). However, the concentration of Zn (1.72 mg kg^{-1}) was less than the maximum pollutant limit of 300–600 mg kg^{-1} in India (Awashthi 2000). This suggests that continuous greater rates of sludge ($\geq$6 t ha^{-1}) may increase the Zn in soil. This may be because metals in organic wastes are organically bound and the treatment of irradiation may alter their fate (Wen et al. 2002). It has been suggested that Cu and Zn were more mobile in sludge-amended soil compared to other heavy metals, which might decrease their solubilization, leaching, and availability to plants (Antolin et al. 2005). Thus, application of sludge may supply Zn in soil and might be useful in the soil that is restricted in Zn. In contrast to this, Kirkham (1980) observed no change in Zn concentration by sludge irradiation. There was no significant increase in the metal concentration in soil after fertilizer applications in comparison to before fertilizer treatments (Tables 3 and 9).

The concentrations of heavy metals in soil were less than the maximum pollutant limits set by the U.S. EPA (1993) and EU of 300–400, 750–1200, and 20–40 mg kg^{-1}, respectively, for Ni, Pb, and Cd and also of 2500–4000 mg kg^{-1} for Zn (Dewil, Baeyens, and Neyens 2006; Table 9). In a similar study to understand the accumulation of heavy metals in soil, Korboulewsky, Dupouyet, and Bonin (2002) studied the effect of sewage sludge applied at rates of 10, 30, and 90 t ha^{-1} and found that soil organic matter increased in all the treatments, but there was no increase in total or available heavy-metal concentrations of soil. El Montium and Badawy (2002) and Gerzabek, Lombi, and Herger (1999) observed increased contents of DTPA-extractable Cd, Co, Ni, and Pb in soil and fractions of Cd, Cu, and Zn in the substrate with applications of irradiated or nonirradiated sewage sludge.

In a long-term study, McBride et al. (1999) observed that Zn, Cd, and Cu in percolates at 60 cm deep were in a complex form with dissolved organic matter. Long-term application of sewage sludge limited by N and P fertilizer application may cause a gradual increase in the concentration of heavy metals in sludge-amended soils. In this study, there was no increase in heavy-metal content of experimental soil supplied with sludge. However, it has to be noted that in this study, the heavy-metal accumulation in soil was measured during the years of sludge application (i.e., after harvesting of crop, but in the same year). Research on the behavior of heavy metals that have approached equilibrium years after sludge application is required to understand the long-term effect of treated and untreated sludge on agricultural farms.

Conclusion

A rational use of sludge aims to take the advantage of nutrient source and to avoid any negative consequences such as heavy-metal accumulation in soil.

Table 8

Influence of various sources and levels of fertilizers on soil metallic micronutrients

	DTPA Zn (mg kg^{-1})			DTPA Mn (mg kg^{-1})			DTPA Fe (mg kg^{-1})			DTPA Cu (mg kg^{-1})		
Treatment	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled
Source of fertilizers (S)												
S_1	1.25	1.38	1.32	13.22	12.51	12.86	5.44	5.55	5.49	1.64	1.61	1.63
S_2	1.43	1.42	1.43	13.15	12.04	12.60	5.50	5.62	5.56	1.68	1.64	1.66
S_3	1.43	1.40	1.41	13.38	12.63	13.00	5.69	5.75	5.72	1.73	1.76	1.75
SE (±)	0.08	0.08	0.08	0.29	0.22	0.26	0.10	0.10	0.10	0.07	0.07	0.07
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of fertilizers (L)												
L_1	1.27	1.29	1.28	13.21	12.58	12.89	5.58	5.70	5.64	1.72	1.71	1.71
L_2	1.22	1.25	1.23	13.18	12.17	12.67	5.53	5.53	5.53	1.72	1.68	1.70
L_3	1.74	1.70	1.72	13.56	12.41	12.99	5.59	5.70	5.64	1.57	1.53	1.55
L_4	1.21	1.35	1.28	13.33	12.80	13.06	5.48	5.59	5.53	1.67	1.63	1.65
L_5	1.33	1.36	1.35	12.60	12.10	12.35	5.57	5.72	5.64	1.73	1.69	1.71
L_6	1.43	1.46	1.44	13.62	12.30	12.96	5.51	5.60	5.55	1.69	1.80	1.74
SE (±)	0.11	0.11	0.05	0.41	0.31	0.18	0.15	0.14	0.07	0.10	0.11	0.05
CD @ 5%	0.31	NS	0.15	NS	NS	NS	NS	NS	NS	NS	NS	NS
S × L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	23.71	23.71	23.71	9.34	7.58	8.57	8.04	7.41	7.73	17.78	18.89	18.34
Pollutant limit[a]		300–600			—			—			135–270	

[a]Source: Awashthi (2000).

Table 9

Influence of various sources and levels of fertilizers on soil heavy metals

	DTPA Ni (mg kg^{-1})			DTPA Pb (mg kg^{-1})			DTPA Cd (mg kg^{-1})			DTPA Co (mg kg^{-1})		
Treatment	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled	2005–06	2006–07	Pooled
Source of fertilizers (S)												
S_1	0.33	0.34	0.33	0.44	0.45	0.45	0.13	0.15	0.14	0.29	0.31	0.30
S_2	0.33	0.33	0.33	0.42	0.44	0.43	0.14	0.15	0.14	0.29	0.30	0.30
S_3	0.33	0.34	0.33	0.46	0.47	0.46	0.13	0.15	0.14	0.30	0.32	0.31
SE (±)	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of fertilizers (L)												
L_1	0.31	0.32	0.32	0.43	0.44	0.44	0.13	0.15	0.14	0.30	0.32	0.31
L_2	0.32	0.32	0.32	0.46	0.49	0.48	0.13	0.15	0.14	0.30	0.32	0.31
L_3	0.33	0.34	0.33	0.41	0.41	0.41	0.13	0.15	0.14	0.31	0.32	0.31
L_4	0.36	0.37	0.36	0.44	0.44	0.44	0.14	0.16	0.15	0.30	0.32	0.31
L_5	0.33	0.34	0.33	0.47	0.50	0.49	0.14	0.15	0.15	0.28	0.29	0.29
L_6	0.33	0.33	0.33	0.42	0.43	0.43	0.12	0.14	0.13	0.29	0.30	0.30
SE (±)	0.02	0.02	0.01	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
CD @ 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S × L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	16.38	16.38	16.38	21.22	21.29	21.26	17.78	15.25	16.44	9.39	10.24	9.85
Pollutant limit[a]		75–150			250–500			3–6			—	

[a] Source: Awashthi (2000).

The present experiment was carried out to evaluate manurial value of GISS in comparison to conventional FYM and its impact on soil chemical properties. The chemical analysis of all three fertilizers revealed that the heavy-metal content in GISS and NISS were below the maximum limit of U.S. EPA and EU standards. Study results demonstrated that both sewage sludges (GISS and NISS) were similar with respect to radish yields. Irradiation had no adverse effect in terms of crop yield and uptake of nutrients. The present results also suggest that the GISS was as good as the conventional FYM and has potential to be a cheap source of major (especially P in this study) and micronutrients (Zn in this study) for radish crop growth. With respect to application rates of fertilizers, the radish yield was nonsignificant; this suggests that the sewage sludge has potential to be an alternative to FYM, even at lower application rates. Physicochemical properties of soil were not altered as a result of any of fertilizers used. In this 2-year study, accumulation of heavy metals derived from sewage sludge in soil were found to be far lower than the maximum limit prescribed by the U.S. EPA and the EU. No phytotoxic effect was noticed on radish plants during the years of experimentation.

The accumulation of heavy metals in soil was not noticed in this experiment and thus the irradiated sewage sludge used in present study seemed to be comparable to FYM. There was no significant yield difference at greater rates of fertilizer application, which suggests that the lower application (6 t ha^{-1}) of sewage sludge would be cheaper. However, we suggest that the research on fate and behavior of heavy metals in a long-term use of sewage sludge in different soil types is needed to understand the long-term impact of irradiated sewage-sludge application on agricultural land and crop products before its commercial use.

References

Ahmed, A. U., and D. L. Sorensen. 1997. Auto heating and pathogen destruction during storage of dewatered biosolids with minimal mixing. *Water and Environment Research* 69:81–94.

Ailincai, C., G. Jitarcanu, D. Bucur, and D. Ailincai. 2007. Influence of sewage sludge on maize yield and soil chemical characteristics. *Journal of Food, Agriculture and Environment* 5:310–313.

Antolin, M. C., I. Pascaul, C. Garcia, A. Polo, and M. Sanchez-Diaz. 2005. Growth, yield, and solute content of barley in soils treated with sewage sludge under semiarid Mediterranean conditions. *Field Crops Research* 94:224–237.

Athalye, V. V., V. Ramachamdran, D. U. Patel, and T. J. D'Souza. 1999. Uptake of macronutrients and heavy metals by maize-green gram crops from Inceptisols amended with normal and irradiated sewage sludge. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project 20–24 September, Malaysia.

Awashthi, S. K. 2000. Prevention of Food Adulteration Act 37 of 1954. *Central and state rules as amended for 1999*, 3rd ed. New Delhi, India: Ashoka Law House.

Bauer, R. 1994. Application of solar radiation for photochemical wastewater treatment. *Chemosphere* 29:1225–1228

Borrely, S. I., A. C. Cruz, N. L. DelMastro, M. H. O. Sampra, and E. S. Somessari. 1998. Radiation processing of sewage and sludge. *Review of Progress in Nuclear Energy* 33:3–21.

Boswell, F. C. 1975. Municipal sewage sludge and selected element application to soil: Effect on soil and fescue. *Journal of Environmental Quality* 4:267–272.

Campanella, L., T. Ferri, B. M. Petronio, and A. Piccolo. 1989. Effect of speciation in sludges on the adsorption of leached metals from soil. *Science of the Total Environment* 79:223–231.

Chandel, S. R. S. 1970. *A handbook of agricultural statistics*, 4th ed. Kanpur, India: Achal Prakashan Mandir Parmat.

Chitdeshwari, T., P. Savithi, and S. Mahimairaja. 2002. Effect of sewage biosolid composts on the yield of crops. *Indian Journal of Environmental Protection* 21:911–912.

Commission of the European Communities. 1986. Council directive 86/278/EEC on the protection of the environment and in particular of the soil, when sewage sludge is used in agriculture. *Official Journal of European Communities* L181/6.

Danish Ministry of Environment and Energy. 1996. *Statutory application of waste products for agricultural purposes*, No. 823, Annx. 2, Copenhagen, Denmark.

Dewil, R., J. Baeyens, and E. Neyens. 2006. Reducing the heavy metal content of sewage sludge by advanced sludge treatment methods. *Environmental Engineering Science* 23:994–999.

El Motaium, R. A., and S. H. Badawy. 2002. Heavy metal (Cd, Co, Ni, and Pb) accumulation in tomato plants and soils amended with irradiated and nonirradiated sewage sludge. *Egyptian Journal of Soil Science* 42:521–543.

Epstein, E., J. M. Taylor, and R. L. Chaney. 1976. Effects of sewage sludge and compost applied to soil on some soil physical and chemical properties. *Journal of Environmental Quality* 5:422–426.

Fauziah, C. I., and A. B. Rosenani. 1999. Domestic sewage sludge application to corn after five cycles: Effect on yield and elemental uptake and accumulations in the soil. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project on the Use of Irradiation Sewage Sludge to Increase Soil Fertility and Crop Yields and to Preserve the Environment, 20–24 September, Malaysia.

Gautam, S., M. R. Shah, S. Sunil, and S. Arun. 2005. Gamma irradiation of municipal sludge for safe disposal and agricultural use. *Water and Environment Research* 77:472–479.

Gerzabek, M. H., E. Lombi, and P. Herger. 1999. Use of sewage sludge in Austria, II: N-availability and heavy-metal uptake. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project on the Use of Irradiation Sewage Sludge to Increase Soil Fertility and Crop Yields and to Preserve the Environment, 20–24 September, Malaysia.

Getoff, N. 1992. Radiation processing of liquid and solid industrial wastes. In *Proceedings of Application of Isotopes and Radiation in Conservation of the Environment*, 153–159. Vienna, Austria: International Atomic Energy.

Getoff, N. 1996. Radiation-induced degradation of water pollutants: State of the art. *Radiation Physics and Chemistry* 47:581–593.

GOI (government of India). 2002. *Water supply and sanitation: A WHO-UNICFF sponsored study*. Planning Commission, Government of India, New Delhi.

Harrison, E. Z., M. B. McBride, and D. R. Bouldin. 1999. Land application of sewage sludges: An appraisal of the US regulation. *International Journal of Environment and Pollution* 11:1–36.

Hashimoto, S., K. Nishimura, W. Kawakami, and H. Watanabe. 1986. Disinfection of sewage sludge cake by an electron accelerator. *Journal of Fermentation Technology* 64:299–304.

Hornick, S. B., L. J. Sikora, S. B. Sterrett, J. J. Murray, P. D. Millner, W. D. Burge, D. Colacicco, J. F. Parr, R. L. Chaney, and G. B. Willson. 1984. *Utilization of sewage sludge compost as soil conditioner and fertilizer for plant growth* (Agriculture Information Bulletin No. 464). Washington, D.C.: U. S. Department of Agriculture.

Jackson, M. L. 1973. *Soil chemical analysis*. New Delhi, India: Prentice-Hall of India Pvt. Ltd.

Jung, M. C., I. Thornton, and H. T. Chon. 2002. Arsenic, Sb, and Bi contaminations of soils, plants, waters, and sediments in the vicinity of the Dalsung Cu-W mine in Korea. *Science of the Total Environment* 295:81–89.

Kapila, S., R. S. Puranam, N. N. Rao, V. V. Modi, R. Ekbote, and M. N. Shah. 1981. Some aspects of hygienization of sewage sludge. In *Proceedings of the National Symposium on Applications of Nuclear and Allied Techniques in Public Health and Pollution Control*, 45–54. Mumbai, India: Bhabha Atomic Research Centre, Department of Atomic Energy.

Kirkham, M. B. 1980. Availability of metals in irradiated sewage sludge. *Journal of Agricultural and Food Chemistry* 28:663–665.

Korboulewsky, N., S. Dupouyet, and G. Bonin G., 2002. Environmental risks of applying sewage sludge compost to vineyards: Carbon, heavy metals, nitrogen, and phosphorus accumulation. *Journal of Environmental Quality* 31:1522–1527.

Krogman, U., L. S. Boyles, C. J. Martel, and K. A. McComas. 1997. Biosolids and sludge management. *Water Environment Research* 69:534–549.

Lessel, T. H. 1988. *Disinfection of sewage sludge by gamma irradiation and alternative methods*. IAEA-TECDOC-454 in Technical and economic comparision of irradiation and conventional methods. IAEA Advisory Group Meeting, October 6–8, Dubrovnic, Yugoslavia, 179–188.

Lowe, H. N., W. G. Lacy, B. F. Surkiewicz, and R. F. Yaeger. 1956. Destruction of microorganisms in water, sewage and sewage sludge by ionizing radiation. *Journal of American Water Works Association* 48:1363–1372.

Magnavacca, C. 1999. Evaluation of irradiated sewage sludge as an industrial crop fertilizer using nuclear techniques. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project on the Use of Irradiation Sewage Sludge to Increase Soil Fertility and Crop Yields and to Preserve the Environment, 20–24 September, Malaysia.

McBride, M. B., B. K. Richards, T. Steenhuis, and G. Spiers. 1999. Long-term leaching of trace elements in a heavily sludge-amended silty clay loam soil. *Soil Science* 164:613–623.

McCaslin, B. D., and G. A. O'Connor. 1982. *Potential fertilizer value of gamma-irradiated sewage sludge on calcareous soils* (Agricultural Experiment Station Bulletin No. 692). Las Cruces, New Mexico: New Mexico University.

Mitrosuhardjo, M. M., S. Syamsu, H. Harsojo, H. Hardiwikarta, and N. Hilmy. 1999. Effect of irradiated sewage sludge on soil and yield of chile pepper. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project on the Use of Irradiation Sewage Sludge to Increase Soil Fertility and Crop Yields and to Preserve the Environment, 20–24 September, Malaysia.

Mor, S., R. Khaiwal, A. D. Visscher, R. P. Dahiya, and A. Chandra. 2006a. Municipal soil waste characterization and its assessment for potential methane generation: A case study. *Science of the Total Environment* 371:1–10.

Mor, S., R. Khaiwal, A. D. Visscher, R. P. Dahiya, and A. Chandra. 2006b. Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site. *Environmental Monitoring and Assessment* 118:435–456.

Neyens, E., and J. Baeyens. 2003a. A review of thermal sludge pre-treatment processes to improve dewaterability. *Journal of Hazardous Material* 98:51–67.

Neyens, E., and J. Baeyens. 2003b. A review of classic Fenton's peroxidation as advanced oxidation techniques. *Journal of Hazardous Material* 98:33–50.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus: Phosphorus soluble in sodium bicarbonate. In *Methods of soil analysis, part 2*, 2nd ed., ed. A. L. Page et al., 421–422. Madison, Wisc.: ASA and SSSA.

OMAF (Ontario Ministry of Agriculture and Food). 1990. *Field crop recommendations* (Publication 296). Ottawa: Ontario Ministry of Agriculture and Food.

OMEE (Ontario Ministry of Environment and Energy). 1996. *Guidelines for the utilization of biosolids and other wastes on agricultural land*. Ottawa, Canada: Ontario Ministry of Environment and Energy.

Pandya, G. A., S. Banerjee, and V. V. Modi. 1991. Perspectives of recycling gamma-irradiated sewage sludge in agricultural application: A study on methi (*Trigonella foenum-graecum* L.: *leguminosae*). *Environmental Pollution* 72:225–237.

Pandya, G. A., P. D. Prakash, and V. V. Modi. 1988. Effect of gamma-irradiated sludge on the growth and yield of rice (*Orysa sativa* L. var. GR-3). *Environmental Pollution* 51:63–73.

Pandya, G. A., S. Sachidanand, and V. V. Modi. 1989. Potential of recycling gamma-irradiated sewage sludge for use as fertilizer: A study on chickpea (*Cicer arietinum*). *Environmental Pollution* 56:101–111.

Pikav, A. K., and V. N. Shubin. 1984. Radiation treatment of liquid waste. *Radiation Physics and Chemistry* 24:77–97.

Pike, E. B. 1986. Pathogens in sewage sludge (I): Agricultural use of sewage sludge and the control of disease. *Water Pollution Control* 85:472–477.

Rathod, P. H., J. C. Patel, M. R. Shah, and A. J. Jhala. 2008. Evaluation of gamma irradiation for bio-solid waste management. *International Journal of Environment and Waste Management* 2:37–48.

Rawat, K. P., A. Sharma, and S. M. Rao. 1998. Microbiological and physicochemical analysis of radiation disinfected municipal sewage. *Water Research* 32:737–740.

Sommers, L. E. 1977. Chemical composition of sewage sludge and analysis of their potential use as fertilizers. *Journal of Environmental Quality* 6:225–232.

Stevenson, F. J. 1982. *Humus chemistry: Genesis, compositions, reactions: Degradation products and chemical structures*. New York: Wiley.

Swinwood, J. F., and F. M. Fraser. 1993. Environmental disinfection of sewage waste water and sludge by electron treatment. *Radiation Physics and Chemistry* 24:55–56.

Swinwood, J. F., T. D. Waite, P. Kruger, and S. M. Rao. 1994. Radiation technologies for waste treatment: A global perspective. *IAEA Bulletin* 36:11–15.

Tsadilas, C. D., T. Matsi, N. Barbayiannis, and D. Dimoyiannis. 1995. Influence of sewage sludge application on soil properties and on the distribution and availability of heavy metal fractions. *Communications in Soil Science and Plant Analysis* 26:2603–2619.

Tyler, L. D., and M. B. McBride. 1982. Mobility and extractability of cadmium, copper, nickel, and zinc in organic and mineral soil columns. *Soil Science* 134:198–205.

USEPA (U.S. Environmental Protection Agency). 1993. *Environmental regulations and technology: Use and disposal of municipal wastewater sludge* (USEPA 503.48). Washington, D.C.: U.S. Government Printing Office.

Waite, T. D., P. Kruger, E. Bryan, and J. F. Swinwood. 1992. Irradiation treatment of water and waste. In *Proceedings of Application of Isotopes and Radiation in Conservation of the Environment*, 143–152. Vienna, Austria: International Atomic Energy.

Wang, J., and J. Wang. 2007. Application of radiation technology to sewage sludge processing: A review. *Journal of Hazardous Materials* 143:2–7.

Welch, J. E., and L. J. Lund. 1987. Soil properties, irrigation water quality, and soil moisture level influences on the movement of nickel in sewage sludge–treated soils. *Journal of Environmental Quality* 16:403–410.

Wen, G., T. E. Bates, and R. P. Voroney. 1995. Evaluation of nitrogen availability in irradiated sewage sludge, sludge compost, and manure compost. *Journal of Environmental Quality* 24:527–534.

Wen, G., T. E. Bates, R. P. Voroney, T. Yamamoto, J. Cjikushi, and D. Curtin. 2002. A yield control approach to assess phytoavailability of Zn and Cu in irradiated, composted sewage sludge and composted manure in filed experiments, I: Zinc. *Plant and Soil* 246:231–240.

Wen, G., R. P. Voroney, and J. P. Winter. 1997. Effects of irradiation on sludge organic carbon and nitrogen mineralization. *Soil Biology and Biochemistry* 29:1363–1370.

WWAP. 2003. *Water for people, water for life, The United Nations World Water Development Report*. UNESCO Publishing (retrieved from http://unesdoc.unesco.org/images/0012/001295/129556e.pdf); co-published with Berghahn Books, UK.

Zhou, L. X., Y. C. Xu, T. H. Jinag, S. J. Zheng, and H. L. Wu. 1999. Characterization of irradiated sewage sludge and its effect on soil fertility, crop yields, and nutrient bioavailability. Paper presented at the Fourth Research Co-ordination Meeting of the FAO/IAEA Co-ordination Research Project on The Use of Irradiation Sewage Sludge to Increase Soil Fertility and Crop Yields and to Preserve the Environment, 20–24 September, Malaysia.