History and prospects of irradiation treatment of sewage sludge

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Abstract This paper presents a survey of irradiation treatment of sewage sludge in the world. Since the first sludge irradiation plant was built in Geiselbullach, West Germany in 1973 which used ^{60}Co as irradiation source, many sludge irradiators were constructed in USA, India, Japan, Canada, Poland and so on, which used ^{60}Co, ^{137}Cs or electron beam as irradiation sources. Some basic researches on irradiation treatment of sewage sludge are, respectively, reviewed, including optimization of irradiation parameters, synergistic effect of radiation with heat, oxygenation, irradiation-composting and potential applications of treated sludge. Some proposals have been suggested for further development of this technology.
Keywords Sewage sludge, Irradiation, γ-ray, Electron beam

1 Introduction

Sewage sludges mainly come from ground surface of city river and biochemical sediment after biochemical treatment of a variety of iffluents, especially from puvalty farms. It represents a renewable resource with great economic significance and has a high concentration of nitrogen and phosphorus and a wide spectrum of trace elements for efficient growth and yield of crops in agricultural practice. In addition, the high content of organic matter (15%) in sludge make it valuable in agronomic applications. Typical analysis of organic and trace element contents of sludge is shown in Table 1 given by Indian scientists.

Table 1 Typical compositions of liquid digested sludge

Dry matter content (D M)/%	4.30
Organic substance (% of D M)	50.00
Inorganic substance (% of D M)	50.00
Nutrients:	
Total-N(% of D M)	5.30
NH_4^+-N(% of D M)	2.50
P(% of D M)	3.20
K(% of D M)	0.4
Ca(% of D M)	8.0
Mg(% of D M)	1.00
Trace elements	
Na/$\mu g \cdot g^{-1}$	2000
Mn/$\mu g \cdot g^{-1}$	200
Cu/$\mu g \cdot g^{-1}$	370
Zn/$\mu g \cdot g^{-1}$	300
Total organic carbon(% of D M)	15.2

However, untreated sludge is a potential hazard to human health and environment as it contains a high concentration of pathogenic agents that include parasites, bacteria and viruses. Release of sewage sludge without disinfection into the environment have been shown to be responsible for the contamination of soil, food supplies and usable water resources. Conventional sludge processing techniques, such as liming, aerobic and anaerobic treatment, composting and digestion, do not provide adequate reduction in pathogens and, particularly, not effectively destroy the eggs of parasites. For instance, in the process of composing, bacterial oxidation results in elevated temperatures and this brings about a certain reduction in the pathogen content. The resulting compost, however, has limited agriculture application. Thermal disinfection is an energy intensive process and is generally considered to be expensive. Treating sludge by irradiation promises a safe, efficient and controllable reduction in pathogen levels to give a sludge product that is highly useful in agriculture.

2 Summary on sewage sludge irradiation plants in the world

The first sewage sludge irradiation plant in a technical scale was constructed in 1973 in Gesiselbullach, West Germany, where ^{60}Co was used as the source material. The plant was designed with a fully automatic operation during

Manuscript received date: 1998-04-10

24 h and high availability. In 1984, ^{137}Cs was added to the facility to supplement the existing ^{60}Co sources.

In the United State, a 7, 250 kg/d irradiator was constructed in 1978 by Sandia National Laboratories in Albuqnerque, New Mexico[2]. At this facility, ^{137}Cs was used as the source material. In 1976, an electron beam irradiation system was put on-line at Boston's Metropolitan District Commission Wastewater Treatment Plant at Deer Island.[3] The facility handled up to 15.8 m^3/h of liquid sludge, delivered a dose of 4 kGy and was primarily used for research purposes. Electrons were generated by a 750 kV, 50kW commercial electron accelerator. A 2 mm thick sheet of sludge was irradiated as it passed over the top of a rotating stainless drum. Unlike the γ irradiation in West Germany and New Mexico, a thin layer of sludge must be produced due to limited penetration capability of the electron beam. However, electron beam is much more efficient in power compared to γ-rays, because it has high ionization density and high treatment capacity.

Based on Deer Island's experience, the Miami-Dade Water and Sewage Authority in Florida decided to locate a sludge irradiator using accelerated electron at its Virginia Key Wastewater Treatment Plant.[3] This irradiator officially began operation in Sept 1984. The electrons are accelerated to an energy of 1.5 MeV and maximum beam width is 1.2 m. The dose is 3.5~4 kGy. A thin layer is obtained by cascading the sludge over a weir-type arrangement, thus forming a curtain of sludge approximately 4 mm thick. This sludge handling system has a flow of 27 m/h and the sludge contains 2% dried solids. The installation at Virginia Key can treat 20%~25% of the total sewage sludge produced at the plant. Space is provided to allow the setup of three more accelerators for expansion to the total sludge production. Irradiated sludge is conditioned with polymer and dewatered by centrifuges. The sludge is stored for several months to dry up. Ultimately, the sludge is screened and distributed for agricultural use.

In Japan, irradiation treatment of sewage sludge has mainly been carried out by Takassaki Radiation Chemistry Research Establishment, Japan Atomic Energy Research Institute.[4] There is an apparatus for electron beam irradiation. Sludge cake (water content 80%) is spreaded on a stainless steel conveyer through a flat nozzle and disinfected by electron beam from upside of the apparatus. The width of the nozzle is 20 cm and sludge thickness is variable from 1~10 mm. The maximum feed rate is 300 kg/h. The electron accelerator used for irradiation is of Cockcroft-Walton type. Its maximum beam energy and current are 2 MeV and 30 mA respectively.

The research on irradiation treatment of sewage sludge in India was mainly done by Bhabha Atomic Research Center (BARC) in Bombay. The pilot scale project was taken up by BARC in collaboration with local agents for setting up an irradiation treatment plant at Baroda, A city in Western India[5]. The features of irradiation treatment plant is shown in Table 2.

Table 2 Features of irradiation treatment plant proposed at Baroda, India

Sludge processing rate (max)	~	$110 m^3 \cdot d^{-1}$
	~	(4%~6% solid)
Treatment dose	~	3~3.5 kGy
Pathogen reduction:		
Bacteria	~	6~7 log units
Viruses	~	1 log units
Installed activity (max)	~	185PBq
Sources utilization period	~	20 a
Shield design capacity	~	37 PBq
External radiation level	~	$2.58 \times 10^3 C/kg \cdot h$
Provision to store and transfer source to a safe location		

In Poland, electron beam irradiation of sewage sludge has been developed in recent years. In Otwork, an irradiation facility for accelerator irradiation of municipal sewage and sludge was built up with a dose of 5kGy. Total investment is 4 million U S dollar. Daily treatment capacity is 48,000m^3 (30% solid content).

Irradiation treatment plants of sewage sludge have also been built up in some other countries in the world, for instance, Canada. and Argentina

3 Some basic research on irradiation treatment of sewage sludge

3.1 Optimization of parameters for radiation hygienisation

Scott and Ahlstron from New Mexico, measured *D*-values (the absorbed dose of radiation required to reduce a population one order of magniture) of selected sludge-borne pathogens (see Table 3).

In China, research on the irradiation treatment of hospital sewage sludge has also been done.[8] Beijing Institute of Environment Protection together with Beijing Tuberculosis Hospital had investigated the radiation sterilization of the sewage and sludge from Beijing Tuberculosis Hospital during 1978~1980. Table 4 shows the experimentally results for minimum radiation lethal dose of various bacteria. The irradiation system for irradiation sterilizing hospital sewage and sludge on the basis of experimentally data had been designed by Beijing Institute of Nuclear Engineering.

Table 3 *D*-value of selected sludge-borne pathogens

Organism	*D*-value/kGy
Bacterium	<0.22~0.36
E coil	1.4
Micrococcus sp	0.36~0.92
Enterobacter sp	0.34~0.47
Salmonalla typhimurium	<0.50~1.40
Proteus mirabilis	<0.22~0.5
Streptococcus faecalis	1.10~2.50
Viruses	1.5~5.0
Poliovirnus	3.5
Coxsackievirus	2.0
Echovirus	1.7
Reovirus	1.65
Adenovirus	1.50
Parasites	
Ascaris sp	<0.66
Fungi	
Aspergillus fumigatis	0.5~0.6

Table 4 Minimum radiation lethal dose of various bacteria in sewage and sludge from tuberculosis hospital (kGy)

Bacteria	Physiological saline	Sewage	sludge
Ascaris eggs	0.8	0.8	1.2
E coil	0.5	1.28	1.7
Typhoid bacillus	1.0	–	1.5
Dysentery bacillus	0.5	–	1.5
Enterobacter aerogenes	0.5	–	1.0
Bovine tuberculosis	0.4	1.0	2.0
Attennualed tuberculosis human	1.0	2.0	2.0
Tuberculosis enriched human	1.0	–	3.0
M phlei	1.63	2.13	4.0

3.2 Synergistic effect of irradiation with other methods

Lessel from Germany investigated the synergistic effect of heat, oxygen, air with irradiation. The most important finding are summarized here.

3.2.1 Combination treatment of heat and irradiation. When ora from the parasite ascaris lnbricoides were placed in 47°C deionized water for 2 h, they remained stable. With ionizing irradiation, a *D*-value of about 0.2 kGy was seen. Combining 47°C heat and radiation yields a *D*-value of about 0.1 kGy.

3.2.2 Combination treatment of oxygenation and radiation. At a dose of 1 kGy, it was found that the inactivation rate was 15 to 38 times higher at an oxygenation concentration of 5 mg/L compared with irradiation without oxygenation. Higher concentration of oxygen in the sludge (15 to 25 mg/L) did not increase the level of disinfection. An oxygenation treatment with a dose of 0.15~0.2 kGy has at least the same effect as 0.3 kGy of irradiation without oxygenation. It is 2 or 3 times more efficient to maintain the O_2 concentration in the sludge by continuous injection of oxygen at a low flow rate than intermittent injection at higher flow rate.

3.2.3 The comparison between γ-ray and electron beam irradiation. The effects of γ-ray and electron beam irradiation are similar. However, electron beam had the advantage of high ionization density, high dose rate, high treatment capacity and high safety. So electron beam might be a better choice for sludge irradiation compared with γ-ray. Japanese scientists investigated the effect of beam energy and sludge thickness on surviving fraction of total bacteria and coliforms. The results show that, to kill bacteria effectively, sludge thickness must be less than 6 mm for beam energy of 2 MeV and 3 mm for 1MeV.

3.2.4 Irradiation-composting.[7] Japanese scientists from Takasaki Radiation Chemistry Research Establishment, JAERI evaluated the economic feasibility of irradiation-composting plant of sewage sludge. Design and cost analysis were made for a sewage sludge treatment plant (capacity of 25~200 ton sludge/day) with an electron accelerator. Dewatered sludge is spread on a rolling drum through a flat nozzle and disinfected by electron irradiation with a dose of 5 kGy. The accelerating voltage of electron and capacity of the accelerator are 1.5 MeV and 15 kW, respectively. Composting cost of the irradiated sludge is also made at the optimum temperature (about 50°C) for 3 d (conventional composting needs 10~12 d). Total volume of the fermentor is about 1/3 of that of conventional composting process because the irradiation makes the time of composting shorter. According to the cost analysis the capital cost of irradiation-composting plant is slightly less than conventional composting plant, when the treatment capacitor is larger than 50 ton/day. Total capacity cost of irradiation-composting plant is lower especially for larger treatment plant because the seale of fermentor is 3 or 4 times smaller. So further research and development would be conducted in Japan using scale pilot pant of 200~300 ton/day capacity.

4 Potential applications of irradiation sludge[6]

Untreated, irradiated and pasteurized sludge were used in agricultural pot and field experiments by German scientists. However, no statistical significant differences were observed in yield, while coin, spring wheat and spring burley were used. In India, properly treated sludge has vast potential applications, especially in agriculture as a complementary product—as a soil conditioner, for augmenting the efficiency of utilization of chemical fertilizers and in animal husbandry as supplementary animal feed, because the Indian economy is still largely based on agriculture and animal husbandry.

4.1 Soil conditioner

The soils get depleted of organic matter through a variety of natural processes, especially in tropical area like India. The high temperature and humidity is suited for the accelerated growth of bacterial population in soil. These bacterial derive energy for their growth from organic matter in soil thus degrading the soil the year round. Frequent and regular addition of organic matter to the soil is therefore very important to maintain and upgrade the soil fertility and crop production. Sludge forms a natural soil conditioner of excellent qualities.

4.2 Fertilizer complement

Chemical fertilizers when combined with sludge will serve as an optimum product for agricultural application. The cultivation of high yielding crops to improve productivity has intensified the application of chemical fertilizers on a large scale. These, however, quickly deplete the soil of organic and micronutrients. Further the uptake of nutrients such as nitrogen and phosphorus from the fertilizer has also been found dependent on various factors, including the carbon balance or organic content of soil. Extensive studies have shown that uptake is generally between 30%~50% even when the best management practices are employed. One way to reduced this waste is to employ an organic-mineral mixture of sludge and chemical fertilizer in a suitable ratio which retains advantages of both and saves on the cost of a part of the chemical fertilizer. This is of considerable economic value to developing countries where fertilizers are often imported. Further with escalating fertilizer costs, the need for a composite product-organic manure with mineral fertilizers has become imperative. Another advantage is the reduction in pollution to the groundwater, as often the unutilised fertilizer nitrates are leached into water by infiltration and surface run-off.

4.3 Animal feed

The use of sludge as animal feed has a great potential. The waste from any town could meet part of its ruminant feed requirements from sewage sludge suitable disinfected.

5 Some proposal for irradiation treatment of sludge in Shanghai[9,10]

Shanghai is a big city in China. Suzhou river is a main river across the city. However, serious contamination by industrial and municipal wastes makes the river dark and smell very bad. The sludges from Suzhou river and biochemical sludge from waste water treatment plant present a big problem in treatment. We suggest a proposal for irradiation treatment of sewage sludge mainly from Suzhou river. The outline of the proposal is as follows:

1) Basic research on irradiation of sewage sludge from Suzhou river including component analysis (organic substances, nutrients, trace elements, variety of bacteria), optimization of parameters for irradiation (the comparison between γ-ray and electron beam, synergistic effect of irradiation and other methods) and comprehensive treatment (irradiation + composting, irradiation + sediment etc)

2) Technological research including flowsheet design and accelerator manufacture. We proposed that an accelerator with electron of 1.5 MeV, 30 mA should be manufactured. If the water content of the sludge is 50% and the dose is 3~5 kGy, the capacity could be 50~100 ton/day.

3) The application of irradiated sludge. As mentioned above, it could mainly be used as composite fertilizer, soil conditioner and animal feed. We prefer its application in agriculture.

6 Summary

1) Sewage sludge represents a renewable resource with great economic significance. However, untreated sludge is a potential hazard to human health and environment as it contains a variety of pathogenic agents.

2) Research over past thirty years has demonstrated that irradiation (γ-ray and electron beam) is an effective means for inactivating pathogens in sewage sludge. Further research and development will be focused on development of appropriate technologies for irradiation plants and estimation of capital cost and treatment cost more precisely.

3) The synergistic effect of irradiation with other methods (heat, oxygen, etc) has been found. It could enhance the treatment efficiency and reduce the treatment cost.

4) Research has demonstrated a vast potential applications of treated sludge, particularly in agriculture as soil conditioner and fertilizer complement and in animal husbandry as supplementary animal feed.

5) A proposal is put forward for irradiation treatment of sludge from Suzhou river of Shanghai

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