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FEASIBILITY ANALYSIS OF A SEWAGE SLUDGE TREATMENT BY AN IRRADIATION PLANT IN MEXICO

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ABSTRACT

Technical and economic analyses of an irradiation plant for sewage sludge treatment determined that an appropriate place for the first sludge electron irradiator in Mexico would be the sewage water treatment plant located north of Toluca in the State of Mexico. This treatment plant is mainly used for domestic wastewater and produces an approximate volume of 70 ton d^{-1} liquid sewage sludge. Considering a 50 kW power of a 10 Mev electron linear accelerator, an irradiation dose of 5 kGy and a treatment capacity of 346 tons per day, it is estimated that the treatment cost would be of $9.00 US dollars per ton.

Palabras clave: lodo residual, planta de tratamiento, tratamiento por irradiación

RESUMEN

Los análisis técnicos y económicos de una planta de irradiación para el tratamiento de lodos residuales permitieron concluir que un lugar adecuado para instalar en México el primer irradiador con electrones para el tratamiento de lodos residuales, es en la planta de tratamiento de aguas ubicada en el norte de la ciudad de Toluca, en el Estado de México. Esta planta trata aguas residuales municipales y genera aproximadamente 70 ton d^{-1} de lodos. Considerando un acelerador de electrones con una potencia de 50 kW y energías hasta de 10 MeV, dosis de irradiación de 5 kGy y capacidad de tratamiento de 346 toneladas por día, se estima que el costo de tratamiento sería de $9.00 dólares americanos por tonelada de lodo.

INTRODUCTION

Wastewater treatment plants yield sewage sludge as a residual product. Sludge contains physical, chemical and biological pollutants that can either represent a major handling problem or an opportunity because of their contents of humus, nitrogen, phosphorus, potassium and other plant nutrient. It also is suitable as a soil conditioner and fertilizer, if properly treated.

Current sludge management systems typically consist of the following processes: thickening, stabilization, dewatering, and disposal. Traditional methods of disposal include incineration, landfills and ocean dumping, but land shortages, high costs and environmental concerns restrict the effectiveness of these methods. Thus, some communities are switching from a philosophy of sludge disposal to one of sludge reuse (Nordion International 1992).

According to Swinwood (1994), sludge is a valuable resource for agriculture and its use is limited by the presence of pathogens and toxic chemicals like heavy metals. Irradiation processes reduce pathogens and destroys some of the organic pollutants; however, radiation does not remove heavy metals.

Therefore, irradiated sludge can be applied to soils only if the contents of heavy metals, pathogens and toxic chemicals are low. At present, only about 10 % of the total wastewater in Mexico is treated (Noyola 1997, Ramírez 1997). However, as a result of the environmental policies of the Mexican Federal Government, the sewage treatment systems will be increased in the near future and to make the panorama worse, the production of sludge will increase as the population does. This problem will be of particular importance in the Metropolitan Zone of Mexico City (MZMC), composed by the Federal District (D.F.) and part of the State of Mexico **(Fig. 1)** with a total population estimated of 25 million inhabitants.

Fig 1. Area studied; State of Mexico, Mexico Metropolitan Zone and Mexico City

According to the Departamento del Distrito Federal (1989), Mazari *et al*. (1992) and Mazari and Mackay (1993) the current water use in the MZMC is 60 $m^3\ s^{-1}$, and there is an increasing demand of almost 45 $m^3\ s^{-1}$. The total wastewater in the MZMC is approximately 81 $m^3\ s^{-1}$. These data show that the wastewater production and therefore the production of sewage sludge will increase in the area.

The number of sewage treatment plants is expected to multiply not only in Mexico City, but all over the country in the next years. Thus, the controlled removal of sludge is considered a major problem by the Mexican authorities.

It is clear that the disinfection of sewage sludge by irradiation helps prevent the diseases caused by these residues (USEPA 1993).

MATERIALS AND METHODS

There is not enough research or experience available to design a sludge irradiator with the purpose of degrading organic toxic compounds. Consequently, the authors have conducted some laboratory treatment experiments in order to identify the main characteristics of such irradiation plant.

Research in Mexico has addressed the reduction of phenols and detergents for the inactivation of coliform bacteria in wastewater (Moreno *et al*. 1992) by gamma radiation, and also in sewage sludge samples from a wastewater treatment plant (Moreno *et al*. 1995). A gamma radiation dose of 7 kGy (1 Gy = gray = 1 J kg^{-1}) decreased six log cycles the total bacteria count, as shown in **figure 2**. Gamma radiation doses between 12 to 18 kGy remove detergents from 71 % to 84 % (**Fig. 3**), and phenols from 55 % to 79 % as demonstrated in **figure 4.** Moreno *et al.*(2000), determined that current sludge contains oil and grease (27 mg kg^{-1}), nitrogen (0.6 mg kg^{-1}), phosphorous (1.1 mg kg^{-1}), phenols (10 mg kg^{-1}), deter-

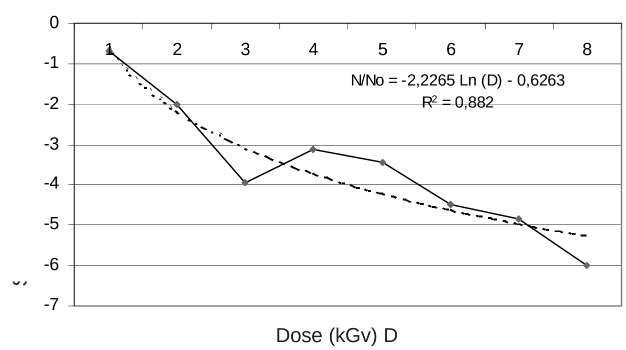

Fig. 2. Total bacterial reduction by gamma irradiation of sewage sludge samples from the same wastewater treatment plant but not from the same day. No = initial bacterial population, N = bacteria survivors

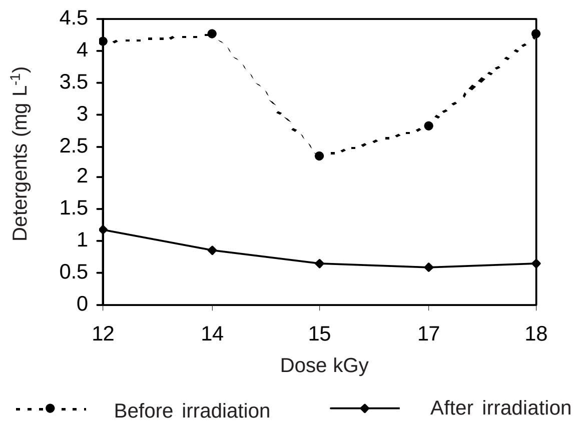

Fig. 3. Detergents reduction by gamma irradiation in sewage sludge samples from the same wastewater treatment plant but not from the same day

gents (124 mg kg^{-1}), full solids (3 %) and water (97 %), and concluded that oil and grease reduce in 33 % using 15 kGy of gamma radiation. Oil and grease are defined as any material recovered as a soluble substance in a solvent. They include other material extracted by the solvent from an acidified sample. Oil and grease are composed of fatty matter from animal and vegetable sources, like palmitic acid (mw = 256.427), petroleum hydrocarbons like benzene (mw = 78.11), xylene (mw = 106.16), and certain organic dyes like dibenzopiridina (mw = 188.2919), among others. Phenols, defined as hydroxy derivatives of benzene, can be present in domestic and industrial wastewater, natural waters, and potable water supplies. A typical example of these later group is paracresol, CH_3-C_6H_4OH, whose molecular weight (mw)

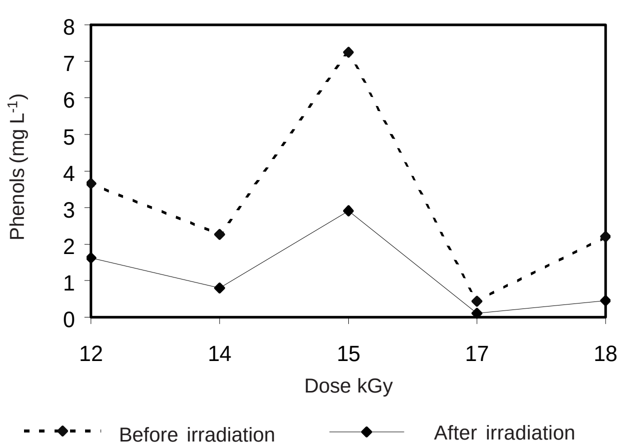

Fig. 3. Phenols reduction by gamma irradiation in sewage sludge samples from the same wastewater treatment plant but not from the same day.

is 108.13 and can be present in certain industrial wastewater as well as in polluted surface waters. Detergents are calculated and reported in terms of the reference material, linear alkyl benzene sulfonate, like sodium dodecyl sulfate, CH_3-$(CH_2)_{11}OSO_3^-Na$ (mw = 288.3768). While the knowledge of the degradation mechanisms of organic toxic compounds are still limited for some of the toxic substances under certain conditions, the inactivation effect and the dose to reduce microorganisms in sewage sludge has been successfully investigated.

Based on the experimental results reported in this study, it is strongly recommended to optimize the industrial process in a pilot plant before building an irradiation plant on a practical scale on the site of an existing sewage water treatment plant.

Tentatively, a sludge irradiation plant in Latin America would be very useful for many research purposes, similar to the irradiation plant in Geiselbullach, Germany (Lessel and Suess 1978, 1984) where an eight-year multidisciplinary research program took place.

An appropriate place for a pilot sludge irradiator in Mexico is the sewage water treatment plant located north of Toluca in the State of Mexico. This treatment plant is devoted to domestic wastewater and produces a constant liquid sewage sludge of approximately 70 tons per day which could feed the electron irradiator. The site is near the National Institute for Nuclear Research (ININ) and the Autonomous University of the State of Mexico (UAEM) in Toluca, thus facilitating the cooperation and joint efforts of both institutions to carry out interdisciplinary research programs. Moreover, it is possible to transport the sludge from the wastewater treatment plant in Eastern Toluca Oriente the proposed treatment plant in Northern Toluca (5 km away).

The U.S. Environmental Protection Agency (USEPA) issued the Standards for the Use or Disposal of Sewage Sludge in the Code of Federal Regulations Part. 503.13 (USEPA 1993), where the limits of pollutant metals for the land application of sewage sludge are established. This code includes metals as cadmium, chromium, copper, lead, nickel, and others. Sludge from both wastewater treatment plants in Northern Toluca (Martín del Campo 1996) and in Eastern Toluca (Gómez *et al*. 1999), have metal concentrations lower than the limits set in 40 CFR, Part. 503.13 (**Table I**). This sewage sludge contains negligible levels of pollutants and ensures that human health and the environment are safe when these sludge is applied to land uses.

Technical considerations of gamma and electron irradiators

Due to the strong public concern about nuclear technology, especially when radioactive material is used, an electron beam technique is an alternative that offers valu-

TABLE I. POLLUTANT LIMITS FOR THE LAND APPLICATION OF SEWAGE SLUDGE AND CONCENTRATIONS OF HEAVY METALS IN SEWAGE SLUDGE FROM BOTH TOLUCA NORTE AND TOLUCA ORIENTE WASTEWATER TREATMENT PLANTS

Pollutant	Ceiling Concentrations* (mg kg^{-1})	Toluca Norte (mg kg^{-1})	Toluca Oriente (mg kg^{-1})
Cadmium	85	4	21
Chromium	300	283	152
Copper	4,300	353	301
lead	840	152	256
Nickel	420	29	77
Zinc	7,500	1327	2215

*(40CFR 503.13)

able safety features thanks to the possibility of switching off the radiation energy at any time without causing any radioactive waste. Thus radioactive sources and accelerators were compared based on their output power. Power is defined as the energy delivered every second and is measured in watts. The output power of radioactive sources and accelerators is calculated as follows: the activity A of a radioactive source is defined as the number of γ-photons per second, then the energy per second (watts) is obtained by multiplying the activity by the energy E of each γ-photon.

Output power of a source Ps

$$Ps = E\left(\frac{MeV}{\gamma}\right)A(MCi)$$

$$Ps = E\left(\frac{MeV}{\gamma}\right)\left[\frac{1.6X10^{-13}\ joules}{MeV}\right]A(MCi)\left[\frac{3.7X10^{16}}{MCi}\frac{\gamma}{s}\right]$$

Where quantities in rectangular brackets are conversion factors.

$$Ps = 5.92\ E\left(\frac{MeV}{\gamma}\right)A(MCi)kwatts \quad (1)$$

Where the constant 5.92 has the unit

$$\left(\frac{\gamma}{MeV\quad MCi}\right)$$

The accelerator-output power P_A is defined as the product of the accelerating voltage V times the number of electrons per second (current) I, this is

Power of accelerator P_A = V (volts) I (A)
or

$$P_A = V(Mvolts)\ I\ (mA)\ kwatts \quad (2)$$

Recent advances in accelerator technology make it attractive as an alternative method to refrain from commercial Co-γ sources. Output power from accelerators is comparable to that of radioactive Co-γ sources through the Bremsstrahlung effect that produces x-rays through the interaction of electrons with a converter metal. The efficiency of x-ray production increases with the atomic number of the metal target and the energy of the electron beam.

The result of equation (2) for a beam from accelerators is shown in **table II**. Due to the low electron penetration in sewage sludge (<1 cm) and the difficulties encountered when producing such thin sludge layers, the electron beam from low energy accelerators (below 2 MeV) restricts practical applications and is regarded as an undeveloped and necessary technology.

TABLE II. OUTPUT POWER OF ACCELERATORS FOR ELECTRON AND X-RAY BEAMS

	Accelerator Electron beam				Electron beam		
Voltage (MeV)	1	2	5	10	1	2	5
Current (mA/m)	10	10	10	10	10	10	10
Efficiency (%)			50		X-Ray beam (converter) 2	4	20
Output Power (P) (kW/m)	5	10	25	50	0.2	0.8	10
Beam Penetration (cm)	0.5	1	2.5	5	2	8	30

The x-ray radiation from the electron beam eight-fold increases depth penetration, but the poor conversion efficiency (4 %) decreases its power in the same extent.

A 5 MeV electron beam on a tungsten converter produces a continuous x-ray spectrum from zero to the electron maximum energy, with a peak of about one tenth of maximum energy. The average penetration of such x-ray spectrum is 30 cm in sewage sludge, comparable to that of Co-60 γ sources. The relatively high conversion efficiency is 20 %, which in terms of output power (according with equation 1) is equivalent to a Co-γ source of 3.5 MCi.

As determined by Moreno *et al.* (2000) an electron beam of 10 MeV has a penetration range of 5 cm in sewage sludge; the energy deposition is not constant and follows the profile shown in **figure 5**. If the electron beam treats a layer 1m wide and 10 cm thick of sewage sludge from both right and left sides, the total dose is the sum of both depth profiles. This arrangement has the advantage of providing a standardized dose (within the accepted experimental error).

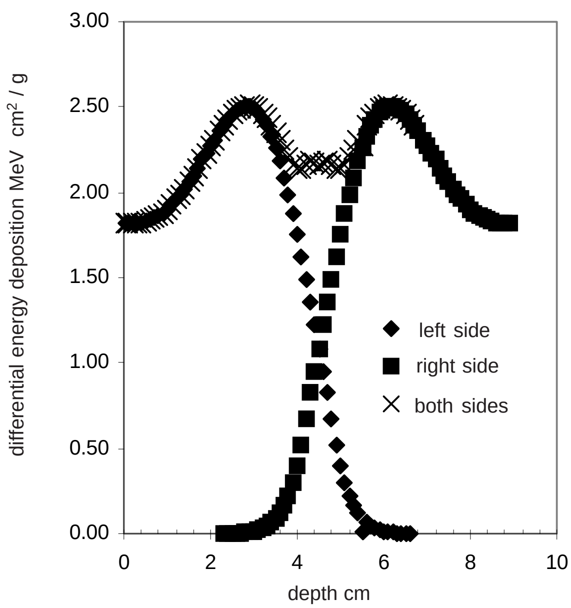

Fig. 5. Differential energy deposition of two 10 MeV electron beam, through both sides of a sewage sludge 9 cm thick

Feasibility of an electron irradiation plant

According to McKeown (1996), using AECL Accelerator's IMPELA Technology of 10 MeV and 50 kW of electron beam power to treat 18,000 tons y^{-1} of sewage sludge, including dewatering, sterilization and drying, has a total cost of $ 12.08 millions of dollars, where approximately 41 % ($ 4.9 millions) account for the disinfection component, 38 % ($ 4.6 millions) for dewatering and 21 % ($ 2.5 millions) for the drying process. McKeown (1996) reported the results of different treatment technologies for a five-year program. The total cost to treat 18,000 tons y^{-1} of sewage sludge including dewatering for electron disinfection was $ 3.7 millions, while the total costs of lime stabilization processes is estimated between $ 3.7 to $5.0 millions, for composting plus lime stabilization $ 3.5 millions, and the costs of drying and pelletization is $ 5.0 millions. McKeown (1996) concluded that radiation technology is competitive with other biological processes for the treatment of sewage sludge.

An alternative to continuous irradiation of a thin sludge layer is the batch operation method, where accelerators with relative low energies of 1.5 MeV and higher can be used during the irradiation treatment. These machines imply significantly lower costs compared to high energy accelerators. However, the batch wise operation with electron beam machines is not yet experienced in practical plants and it has only been tried at in laboratories. Such operation requires additional research in order to get a homogenous dose distribution and so increase the chances for success.

Concerning the research experience on sludge irradiation, Hashimoto (1991) has shown that the bacterial count decreased about 5 log cycles after applying a 5 kGy dose; a 2 kGy irradiation was enough to reduce the coliforms in sewage sludge to an acceptable level.

The research carried out at the Miami pilot plant facility by Kurucz *et al*. (1995), from the University of Florida, has demonstrated the effectiveness of electron-beam waste treatment in toxic chemicals. This paper indicates that under ideal conditions doses in the range between 5 kGy to 10 kGy are required to remove more than 90 % of some toxic organic compounds. Higher doses would certainly be required under practical conditions.

Research by Trump *et al*. (1984) shows that a $<$ 500 Gy dose is adequate for the disinfection of municipal wastewater, while a 4 kGy dose is enough to disinfect sludge.

A 10 MeV 200 kW accelerator could treat 2,300 m^3 day^{-1} using a 500 Gy dose. Chlorine is generally used for disinfection, but it is dangerous considering possible side effects. It is however possible to have satisfactory disinfections at the 500 Gy level with electrons and avoid all side effects. In such case a single accelerator (as the one mentioned above) would be enough to treat the most contaminated wastewater in the region.

A new accelerator technology became available in the last 8 years thanks to the development of industrial accelerators with energies up to 10 MeV, penetration capacity of 4.5 cm in water and the necessary power for a practical throughput.

The technology for handling sludge to suit these new machines has not yet been designed but should be a routine engineering task, which ININ and UAEM can assume and deliver as a major contribution of technology. Capital and operating cost estimations of a sewage sludge treatment plant by irradiation in Mexico were obtained considering the maximum power of the electron linear accelerator of 50 kW and 10 MeV of beam energy, an irradiation dose of 5 kGy, a treatment capacity of 346 ton d^{-1}, 40 % efficiency, an average electricity consumption of 400 kW, an operating mode of 325 days per year, and one shift per day. Total annual operating costs are estimated to be $ 1,007,808 dollars to treat 346 tons d^{-1} with an irradiation dose of 5 kGy. This figure includes both

TABLE III. APPLICATION, ACCELERATOR TYPE, OPERATING MODE AND CAPITAL COST OF A SEWAGE SLUDGE TREATMENT PLANT BY IRRADIATION IN MEXICO

APPLICATION		Financial	
		Accelerator amortization	15 Y
Dose	5 kGy	Shielding amortization	15 Y
Product Depth	3.2 cm	Special item amortization	15 Y
Product Width	80 cm	Interest on accelerator	7 %
Specific Gravity	1 g cm^{-3}	Interest on shielding	7 %
Absorption Efficiency	40 %	Interest on special building items	7 %
ACCELERATOR TYPE		Capital Equipment & Buildings	(U.S. $)
		Accelerator	
Energy	10.0 MeV	Warranty	
Power	50 kW	Installation	
Scan Width	1 m	Proj. Mgmt. & Training	
Electricity Consumption	400 kW	Spare Parts	
		Total accelerator & related	3,796,000
OPERATING MODE		Shipping & Insurance	18,250
Days per year	365 d	Shielding	292,000
Shifts per day	1	Product Handling	400,770
Hours per shift	8 h	Building	365,000
Operating hours per year	2600 h	Special Building Items	483,187
Operator	1		
		TOTAL CAPITAL	5,355,207

capital ($ 663,891 dollars) and operation costs ($ 343,917 dollars). The unit's costs at full swing are $9.0 dollars per ton. The cost estimation is sufficiently detailed and contains explicit information to help investors make a clear appraisal of what the process might cost. Further information to consider the overall costs is provided in **tables III** and **IV**.

Costs cover all kinds of aspects, such as the sludge handling engineering needed in Mexico, transportation means, protection, dosimeters and plant operation. This estimate also takes into consideration the major technical uncertainties the project entails. Mexico is self-reliant to handle this kind of project.

TABLE IV. ANNUAL OPERATING COSTS AND CAPACITY OF A SEWAGE SLUDGE TREATMENT PLANT BY IRRADIATION IN MÉXICO

ANNUAL OPERATING COSTS (U.S. $)		TREATMENT CAPACITY	
CAPITAL COSTS		Cubic meters per day	346
		Cubic meters per year	112,320
Equipment amortization costs	515,837		
Shielding amortization costs	32,060	Tons per day	346
Building amortization costs	40,074	Tons per year	112,320
Equipment maintenance costs (fixed)	75,920		
		Product velocity (cm s^{-1})	1.25
TOTAL CAPITAL COSTS	663,891		
OPERATION COSTS		UNIT COSTS AT MAXIMUM CAPACITY	(U.S. $)
Labor	56,940	Costs per ton	9.0
Electricity	182,208	Costs per cubic meter	9.0
Radio frecuency tube costs	45,552		
Equipment maintenance (variable)	59,217		
TOTAL OPERATION COSTS	343,917		
TOTAL ANNUAL COSTS	1,007,808		

CONCLUSIONS

Irradiation processes are effective both for removing organic chemicals and for disinfecting sewage sludge from a wastewater treatment plant.

Total treatment costs, using an electron linear accelerator with 50 kW of maximum power and 10 MeV of beam energy, are estimated to be $ 9.0 dollars per ton assuming an irradiation dose of 5 KGy.

The success of the complete project in solving the problem of sewage sludge contamination in Mexico requires the active participation of all authorities in an interdisciplinary group.

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REFERENCES

Departamento del Distrito Federal, Mexico City (1989). Estrategia metropolitana para el sistema hidraúlico del valle de México, Departamento del Distrito Federal y Gobierno del Estado de México.

Gómez G., Lugo J., Vaca R. and Balderas M. (1999). Variación de metales pesados en lodos residuales municipales. I Simposium de Vinculación Tecnología-Investigación-Industria, 18 y 19 de Noviembre de 1999, Toluca, México. Memorias, pp. 116-128.

Hashimoto S. (1991). Electron beam disinfection of sewage sludge. Japan Atomic Energy Research Institute. International Conference on Evolution in Beam Applications. Takasaki, Japan, November 5 - 8.

Kurucz C. N., Waite T. D. and Cooper W. J. (1995). The Miami electron beam research facility: a large scale wastewater treatment application. Radiat. Phys. Chem. *45*, 299-308.

Lessel T. and Suess A. (1978). Hygienization of sewage sludge by gamma irradiation-experience with an operating pilot plant. Progr. Water Technol. *10*, 641-652.

Lessel T. and Suess A. (1984). Ten years experience in operation of a sewage sludge treatment plant using gamma irradiation. Radiat. Phys. Chem. *24*, 3-16.

Martín del Campo Ma. G. (1996) Caracterización de lodos residuales de 2 plantas tratadoras de aguas (Toluca norte y EPCCA) del Estado de México para una propuesta de utilización en la agricultura. Tesis de Licenciatura en Biología, Facultad de Ciencias, Universidad Autónoma del Estado de México.

Mazari M., Ramírez C. and Alberro J. (Eds.) (1992). Sociedad Mexicana de Mecánica de Suelos, A. C. Mexico City, pp. 37-48.

Mazari M. and Mackay D. (1993). Potential for groundwater contamination in Mexico City. Environ. Sci. Technol. *27*, 794-802.

McKeown J. (1996). Electron sterilization of sewage sludge: a real case comparison with others processes. Radiat. Phys. Chem. *47*, 469-473.

Moreno A. J., Colín C. A. and Vázquez A. O. (1992). Remoción de fenoles detergentes y coliformes presentes en aguas residuales por medio de irradiación. Rev. Int. Contam. Ambient. *8*, 29-35.

Moreno A. J., Colín C. A., Shiba M. I. and León A. B. (1995). Remoción por irradiación de contaminantes en lodos residuales y su posible uso en la agricultura. Rev. Soc. Quím. Méx. *39*, 415-423.

Moreno J., Colín A. and Gomestagle M. (2000). Irradiación de lodos residuales y su uso en el cultivo de avena. Rev. Soc. Quím. Méx. 44, 219-223.

Nordion International Inc. (1992). Gamma processing of sewage. Sludge bibliography 1990-1991. The Association of International Industrial, Industrial Irradiation, A III No. *23*, 281-294.

Noyola R. A. (1997). Planta de tratamiento de aguas residuales a nivel terciario para reuso. Ciclo de Pláticas “Hacia el Tercer Milenio”, pp 37-59, El Colegio Nacional, México, D. F.

Ramírez T. Z. (1997). Aguas residuales, baños de pureza?. Expansión 15-21.

Swinwood J. F. (1994). Radiation technologies for waste treatment: a global perspective. International Atomic Energy Agency Bull. *36*, 11-15.

Trump J. G., Merrill E. W. and Wright K. A. (1984). Disinfection of sewage wastewater and sludge by electron treatment. Radiat. Phys. Chem. *24*, 55-66.

USEPA (US Environmental Protection Agency) (1993). A guide for land appliers on the requirements of the federal standards for the use or disposal of sewage sludge. 40 CFR PART 503.