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PAN AMERICAN HEALTH ORGANIZATION
WORLD HEALTH ORGANIZATION
-ENVIRONMENTAL HEALTH PROGRAM-

HEALTH AND ENVIRONMENTAL CRITERIA FOR THE UTILIZATION OF SEWAGE SLUDGE ON LAND

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PROLOGUE

Sludge is the material which is removed by settling, flotation, or filtration at various stages of the sewage treatment process. Its chemical, biological and physical characteristics depend on the waste discharged into the sewerage system, the type of sewage treatment, the operation of the plant and the process to which the sludge itself has been subjected. It potentially contains pathogens, heavy metals, organic materials and undesirable chemical elements. Sludge characteristics vary considerably from one location to another and in time within the same plant.

The treatment of sludge may entail reduction in volume by dewatering; the stabilization of organic material; and the reduction or destruction of pathogens and various methods of processing to convert it into more useful products. Chemicals may also be added to make the sludge more manageable and to remove various substances.

It is, thus, possible that sewage sludge properly treated, monitored and applied may constitute a valuable resource for soil conditioning and enhancement, its main value being its nitrogen (N) and its phosphorus (P) content. Unfortunately, some of these same elements may cause ground and surface water pollution if not properly controlled. In addition, potentially harmful sludge constituents from normal operation and toxic discharges by unauthorized persons in sewers and treatment plants create risks to health and potential damage to the environment.

Sludge disposal and management in the industrialized countries presents a challenge to public officials. The high cost of sludge processing, together with the increasingly restrictive environmental regulations which limits traditional methods, such as ocean dumping, and incineration has made land application a frequent alternative. Attempts to bypass the regulations generated several proposals for international transportation of sludge to developing countries. Such attempts seem to have been dwarfed by increasing environmental awareness in these countries. However, as the developing countries proceed to improve sewerage coverage, they will be faced with similar sludge management problems and land application can be a possible if not an interesting alternative.

The application of sludge on land involves many problems of interdisciplinary nature requiring knowledge of public health, medicine, engineering and agronomy. Legislation provides the means for integrating all the above mentioned knowledge into adequate sludge management plans and control measures. These considerations are addressed in this document. The characteristics of sewage sludge and its composition are reviewed, particularly with regard to the concentration of microelements that may affect its usefulness in land application. Alternative sludge treatment methods are presented showing most common processes that can be used prior to application and their relative effect on pathogen reduction and stabilization. The section on health considerations analyzes public health risks in relation to the application of sludge on land in regard to pathogens and the persistence of toxic elements in the food chain and in the environment. The effect of heavy metals and toxic organic compounds on soil chemistry, on plant grown on soil amended land, and on animals raised on such lands are also discussed. The risks from pathogenic organisms present in sludge and their fate and movement through the soil environment are important considerations which merit attention in a sludge management program.

Laws in developing countries with regard to disposal and management of sludge and toxic material are either inexistent or too weak to form the basis on an effective sludge management program. For this reason, the United States laws that applies to sewage management practices are indicated. These laws are still evolving, but give a fair idea of framework for sewage sludge management to protect human health and prevent enviromental pollution.

I trust this technical document which has been extracted from the proceedings of the Workshop on International Transportation and Utilization of Sewage Sludge will be useful to public officials and engineers considering land application of sewage sludge. The contribution of all the participants to the above Workshop is acknowledged in the corresponding sections. Special thanks to George Willson, consultant, Raymond Reid and Fred Reiff, regional advisers of this Organization who originated and edited this document.

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CHARACTERISTICS OF SEWAGE SLUDGE[1]

Origin

Sewage is the wastewater collected from dwellings, businesses and industries in sewers. Before discharge to a stream or lake, the sewage is treated to remove most of the solids (generally less than 0.1% of the wastewater) to prevent pollution. Treatment consists of one or more physical, biological and chemical processes. Primary treatment is the sedimentation of settleable solids and usually removes 50 to 60% of the total solids.

Secondary treatment is done by biological processes. In these processes, microorganisms grown on the suspended and dissolved solids are then removed by either sedimentation or flotation. If a very high quality effluent is needed for discharge, advanced methods of wastewater treatment may be employed to further reduce the solids by physical, chemical or biological means.

The solids removed by the wastewater treatment processes, called sewage sludge, are generally subjected to further treatment prior to disposal or utilization. It was estimated that 30 to 40% of the sludge produced in the United States in 1988 was digested or otherwise processed and spread on agricultural or other land as a low analysis fertilizer or soil conditioner.

Sludge Composition

The real problem with sludge is that not all sludge is "domestic." It may contain low levels of potentially toxic materials, as in many cities, industries dump large quantity of wastes down the sewer resulting in very high levels of metals or toxic organics in sludge. Table 1 shows the range of heavy metal levels found in many sludges, typical median levels reported for several sludge composition surveys, and maximum levels for "domestic" anaerobically digested sludges. Zinc, for example, varies from 500 to 50,000 ppm, a hundred-fold range. The lower levels are typical for sludges from suburban areas.

Sludge contains much higher levels of many elements than do soils, even when the sludge arises from domestic (non-industrial) sources. Recent British surveys have shown a wide range in Co, F, and Mo as well. Thus, all domestic sludges as well as industrially polluted sludges must be analyzed for metals and toxic organics.

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[1] From Workshop papers, "Engineering Considerations in the International Transport and Utilization of Sewage Sludge," by George B. Willson; and "Potential Effects of Sludge - Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney.

Table 1

Concentrations of Selected Trace Elements in Dry Digested Sewage Sludges

Element	Reported Range Minimum	Reported Range Maximum	Typical Median Sludge	Soil Typical Soil	Maximum Domestic Sludges
As,ppm	1.1	230.	10.	-	-
Cd,ppm	1.	3,410.	10.	0.1	25.
Cd/Zn, %	0.1	110.	0.8	-	1.5
Co,ppm	11.3	2,490.	30.	-	200.
Cu,ppm	84.	17,000.	800.	15.	1,000.
Cr,ppm	10.	99,000.	500.	25.	1,000.
F,ppm	80.	33,500.	260.	200.	1,000.
Fe, %	0.1	15.4	1.7	2.0	4.0
Hg,ppm	0.6	56.	6.	-	10.
Mn,ppm	32.	9,870.	260.	500.	-
Mo,ppm	0.1	214.	4.	-	25.
Ni,ppm	2.	5,300.	80.	25.	200.
Pb,ppm	13.	26,000.	500.	25.	1,000.
Sn,ppm	2.6	329.	14.	-	-
Se,ppm	1.7	17.2	5.	-	-
Zn,ppm	101.	49,000.	1,700.	50.	2,500.

(Source: Workshop paper, "Potential Effects of Sludge (Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals and Related Regulatory Guidelines," by Rufus L. Chaney).

Much of the value of sludge for land application is in its fertilizer content and application rates should usually be based on the available nitrogen (N) or phosphorus (P) content to plants. Since potassium is relatively soluble, its concentration is low in the sludge. Sludges should be analyzed for their N and P content as they vary between treatment plants and with time. Unprocessed primary and secondary sludges will typicaly range from 2 to 7% N and 2 to 5% P. Processing usually results in a reduction of these elements due to dilution and/or losses.

Sludge Processing Methods

Sludge is frequently dewatered in order to increase the solids concentration to reduce further processing or transportation costs. The most common methods of sludge dewatering are by centrifuges, vacuum filters, belt presses and filter presses. Their effectiveness for increasing the solids content of the sludge depends on the characteristics of sludge and the amount and type of conditioning chemicals used, machine design and operating conditions. Typical solids concentration obtained with the above devices range from 10 to 40%. Sludge drying beds can produce solids concentrations of 40 to 80%, but are land intensive, for this reason, they are not utilized at large treatment plants.

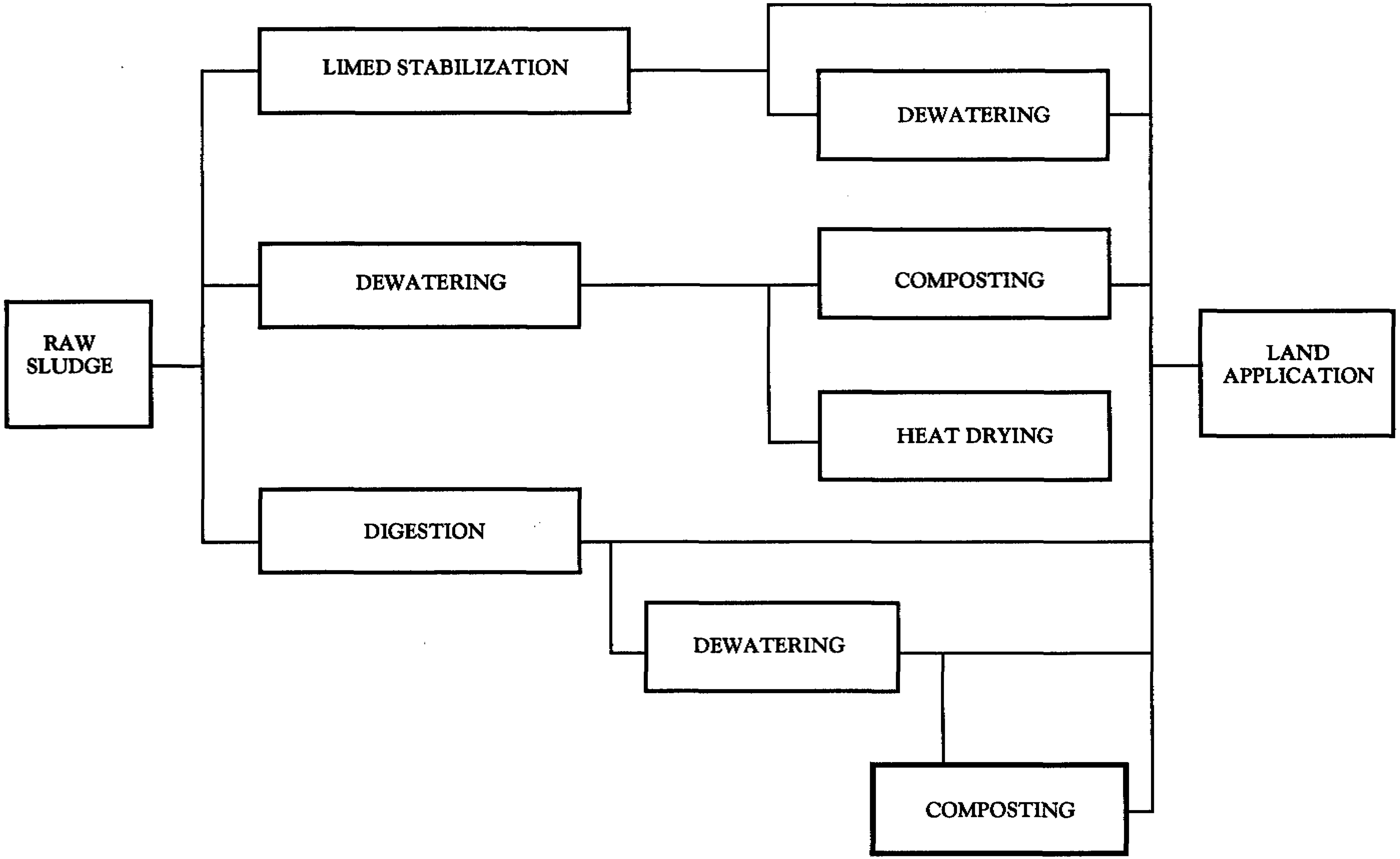
Anaerobic digestion of sludge reduces the volatile solids from 70 to 80% (dry solids basis) to around 50%. This reduces the total amount of any solids that must be handled and results in a concentration of the fertilizer value and also the heavy metals concentrations. Plant availability of N and P in raw or digested sludges is 30 to 50% during the first crop growing season.

Liquid sludges can be easily handled as a fluid by pumps, pipelines and applied to land by irrigation techniques. Pumping requires slightly more power than for water due to a higher viscosity. Dewatered sludges are classified as semi-solids and can usually be pumped with special equipment and specialized operating procedures, but are usually handled with equipment designed for handling granular solids.

In addition to digestion and dewatering, lime stabilization, heat drying and composting are the

Figure 1

SLUDGE TREATMENTS FOR LAND APPLICATION



most common sludge treatment processes used to prepare sludges for land application. The choice of treatment or combination of treatments is a function of operating conditions and costs. Typical treatments or combination of treatments that have been considered acceptable for application to cropland are shown in Figure 1.

Lime stabilization consists of adding sufficient lime to exceed pH 12 for one hour. This treatment has been shown to effectively reduce pathogens to a safe level for land application. Quick lime or hydrated lime are used and dosage ratio may be as high as 0.3 kg lime/kg sludge dry solids. The principal effect of the lime on the handling properties of the sludge is due to increase in solids content contributed by the lime. As lime is commonly used to condition sludge for dewatering, the lime may serve a dual function. Effects of these and other treatment processes are listed in Table 2.

Sludge composting causes the most profound changes in the sludge characteristics of the various sludge treatment processes. The sludge compost is a fine textured solid that may be handled in bulk or bagged. The nitrogen is nearly all in organic form, thus, is more slowly available to plants, typically 10 to 15% per crop season. Thus, compost is more useful than other sludge products as a soil conditioner, but less valuable as a fertilizer. Therefore, *compost would be the preferred sludge product for soil reclamation and improvement projects.*

Table 2

Relative Effects of Various Sludge Treatment Processes on Destruction of Pathogens and Stabilization of Sewage Sludges

Processes	Pathogen Reduction	Putrefaction Potential	Odor Abatement
Anaerobic digestion	Fair	Low	Good
Aerobic digestion	Fair	Low	Good
Chlorination, heavy	Good	Medium	Good
Lime treatment	Good	Medium	Good
Pasteurization (70° C)	Excellent	High	Fair
Ionizing radiation	Excellent	High	Poor
Heat treatment (195° C)	Excellent	High	Poor
Composting (60° C)	Good	Low	Good
Long-term lagooning of digested sludge	Good	-	-

(Source: Farrel, J. B. and G. Stern, 1975, "Methods for Reducing the Infection Hazard of Wastewater Sludge," pp. 19-28. In "Radiation for a Clean Environment," International Atomic Energy Agency, Vienna, Austria).

The solids in sewage sludges usually consist of organic, as well as inorganic material, biological cell masses and chemical coagulants, and contain inorganic elements such as nitrogen, phosphorus, potassium, calcium, and heavy metals. The contents of sludge varies widely from one city to another and often from one treatment plant to another. Within the same city, contents frequently vary with time.

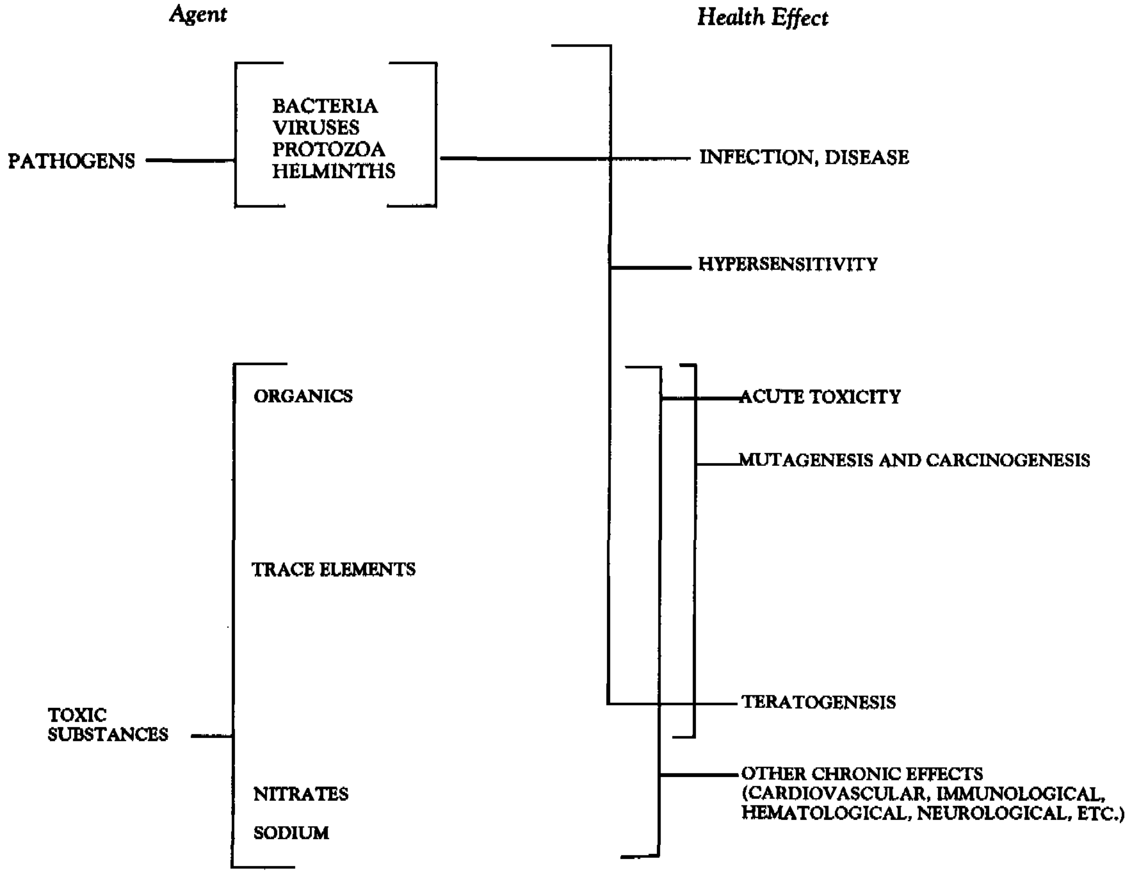
Additional treatment of the sludge through biological digestion, composting, chemical treatment and supplements, and dewatering, drying, or heating also gives rise to variation in characteristics.

HEALTH CONSIDERATIONS[2]

Municipal wastes contain agents of two broad categories that may be harmful to humans: (1) microorganisms from fecal and urinary wastes of humans and other animals; and (2) toxic substances from discarded commercial products and industrial processes. The major human health concerns that arise from each category of agents are shown in Figure 2.

Figure 2

POTENTIALLY HARMFUL AGENTS IN SEWAGE AND THEIR HEALTH EFFECTS



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[2] From Workshop papers, "Public Health Risk and Risk Assessment in Relation to the Management of Municipal Wastes on Lands," by Elmer W. Akin; "Hazards from Pathogens in the United States Sewage Sludges," by W. D. Burge and J. P. Parr; "Potential Effects of Sludge-Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney; and "Long-Term Experience of Sludge Application on Agricultural Lands," by Cord Tietjen.

PATHOGENS[3]

The transmission of infectious diseases has been a long recognized health risk associated with municipal wastes. Outbreaks of disease have been documented by epidemiological investigation when municipal wastes have contaminated drinking and recreational waters. Increased health concern associated with municipal waste has been recently stimulated primarily by (1) the widespread interest in sludge as a desirable soil additive; and (2) the recognition of chronic health effects attributable to a number of inorganic and synthetic organic chemicals. Despite the obvious potential for disease, epidemological studies of land application projects have not verified the risk.

Untreated sewage sludges in the United States may contain pathogenic bacteria, viruses, protozoan cysts and ova of intestinal worms. The kinds of treatments the sludges receive will influence the numbers of these organisms that survive and, consequently, the potential for causing disease. Some of the common bacterial pathogens that may be present are *Salmonella enteritidis, Salmonella typhi, Shigella spp., Vibrio coma, Mycobacterium tuberculosis*, and enteropathogenic *Escherichia coli.* The respective diseases caused by these organisms are salmonellosis, typhoid fever, shigellosis, cholera, tuberculosis and diarrhea. Common viruses isolated from sewage wastes include poliovirus, echovirus, coxsackievirus, reovirus, adenovirus, rotavirus hepatitis A and Norwalk type viruses. The diseases caused by viruses vary from the common cold and gastroenteritis to hepatitis and fatal infections of the central nervous system, and many of the above viruses are capable of producing infections at both ends of the spectrum. Of all the viruses only hepatitis A has been implicated unambiguously in waterborne outbreaks of disease (hepatitis).

The intestinal parasites most often found in sewage of temperate regions are the ova of *Ascaris lumbricoides* (roundworm), *Trichurus trichiura* (whipworm), *Enterobius vermiculus* (pinworm), *Hymenolepis spp.* (dwarf tapeworm), and *Taenia saginata* (beef tapeworm), and cysts of the protozoan *Entamoeba histolytica, Giardia lamblia,* and *Balantidium coli.* Intestinal worm infections are usually subclinical and only become serious in people, usually children, weakened by malnutrition. Protozoan infections most often are subclinical, but can result in diarrhea, sometimes bloody, with extreme weakening of the host. Infections can occur in the liver and other organs.

Obviously for a health effect to result from disease agents in municipal wastewater, means of human exposure must exist. Three routes of exposure appear possible: (1) direct exposure during transport and application, (2) contact with waste-amended soil and/or plants and animals grown on the soil, and (3) ingestion and/or contact with surface or groundwater. When sewage sludges are spread on land, salmonella and possibly shigella bacteria are capable of survival and growth. Salmonellae have been known to persist up to a year. Other pathogenic bacteria may persist for only a few months. Viruses beng incapable of regrowth outside of their host are probably eliminated within three to four months at the most. Protozoan cysts are usually eliminated within a week, but helminthic ova have been known to persist as long as seven years.

The greatest potential for movement of pathogens to surface water, where they might eventually become a source of infection, is associated with the transport of sludge from treated soils during runoff and erosion. Where sewage sludges are applied to soils, it is essential that runoff and erosion be minimized by implementation of recommended soil management and conservation practices.

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[3] From Workshop paper, "Hazards from Pathogens in the United States Sewage Sludges," by W.D. Burge and J.F. Parr, and "Public Health Risk and Risk Assessment in Relation to the Management of Municipal Wastes on Lands," by Elmer W. Atkin.

Persistence

The principal pathogens found in sewage can be divided into four groups: bacteria, protozoa, helminths (intestinal worms), and viruses. Sewage treatment practices reduce the numbers of the above organisms, but evidence is abundant that sludges contain detectable amounts of each of the above four groups. These organisms originally in the wastewater treatment plant influent become associated with the sludge during treatment. The enteric pathogenic bacteria and viruses present in sludge or sludge-amended soils do not have a special stage resistant to destruction, such as the spore forming bacteria and fungi. They must reproduce sooner or later undergo inactivation. Viruses cannot reproduce external to cells of their hosts, and are inactivated at a rate that is directly related to temperature and other factors. Of the pathogenic enteric bacteria, only salmonellae and shigellae are capable of growth in sludge/soil systems, but even these organisms usually face severe microbial competition and potential elimination.

Persistence of viruses is favored by low temperatures, alkaline pH, high levels of soil organic matter and moisture, and shielding from ultra-violet radiation. Presumably, these same conditions also favor bacterial survival. Viruses survival, even when favored by low temperatures in cold climates, probably seldom exceeds three to four months. Coxsackievirus type B3 seeded into sludge applied to soil of a lysimeter study in Denmark was inactivated at a rate of about one log unit per month. In soil flooded with virus seeded sewage sludge and effluent, Poliovirus type 1 survived for 96 days during winter months. The longest survival in the summer was 36 days on spray irrigated vegetables. Most pathogenic bacteria are also eliminated in a few months after application, but salmonellae may persist by regrowth in sludge treated soils. In sludge trenching studies at Beltsville, Maryland, USA salmonellae could still be detected up to about one year, but this can be considered a maximum period for survival.

Factors causing the inactivation of bacteria and viruses in sludge/soil systems have not been extensively studied. However, there is some indication that ammonia concentration and predation are among the most important. Ammonia is produced in sludge/soil systems as a result of microbial decomposition of organic nitrogenous compounds. As the ammonium concentration increases, the pH rises with consequent conversion of a larger amount of the ammonium ion to ammonia gas, which has a high solubility in water. The destruction of viruses has been clearly shown to result from the action of ammonia rather than from a direct effect of high pH. Ammonia is effective in inactivating single stranded RNA viruses, but is not as effective in inactivating double stranded RNA viruses. DNA viruses because of their double stranded nature also should be more resistant to inactivation by NH3.

Nonpathogenic bacteria have been shown to destroy enteric viruses by predation. Predation of pathogenic bacteria in sludge/soil systems by other bacteria and by protozoans and nematodes should also be expected. It is not understood how viruses and pathogenic bacteria are able to persist as long as they do in sludge and sludge-treated soils in the presence of a host of microorganisms requiring nutrients and energy material. Viruses under anaerobic conditions are less susceptible to degradation by microorganism than under aerobic conditions.

Protozoan cysts are susceptible to destruction by drying. Cysts of *Entamoeba histolytica* have been found to persist up to eight days in soil, but for less than three days when exposed on the surface of vegetables. Ascaris ova, however, have been shown to persist for as long as seven years in soil.

Movement of Organisms from Sludge Applied to Soil

When sludges are applied to soil, the bacteria and viruses are intimately associated with the sludge. The vigorous mechanical treatment needed to free viruses from sludge is evidence that they are associated with loose intestinal epithelium initially present in the fecal material. Movement of these organisms with aerosols, at least, from filter-cake sludge would seem unlikely. The greatest potential for movement would be with the sludge and soil during erosion.

Movement of bacteria, viruses, helminthic ova and protozoan cysts with sludge particles, or movement of these organisms independent of the sludge material would necessitate water movement through the sludge. Trenching and subsurface injection of sludge, and to a great extent even mixing of sludge into the soil surface leaves the sludge and soil as discrete entities. Compared to most soils, relatively large forces are required to move water through sludge. The water will tend to move around the sludge and through the soil until the sludge is altered considerably by biological processes.

Movement of Pathogenic Organisms Through the Soil

If pathogenic organisms should be washed from sludge and become associated with the liquid phase, removal by the soil from water during infiltration and percolation constitutes the next barrier against migration to groundwater. Protozoan cysts and helminthic ova are too large to move through most soil-pore systems. Soils would provide an efficient medium for removal of bacteria from infiltrating water and it is hypothesized that viruses also would be effectively removed. More recent work has shown that soils can effectively remove viruses from water, but that under certain conditions both viral and bacterial movement may be extensive. Rapid infiltration systems for renovation of sewage or sewage effluents would be least effective at removing pathogenic organisms, because extremely coarse soils must be utilized to ensure high flow rates.

Bacterial and virus movement may be more extensive than is thought to occur in the agricultural soils of the United States. However, the higher temperatures should reduce the length of pathogen survival in semitropical and tropical zones.

Pathogens Reduction

Sludges that have not been subjected to pathogen reduction by aerobic or anaerobic digestion can be disinfected by other means. Methods commonly used for disinfection include pasteurization, composting, heat-drying, and liming. Pasteurization is used in Germany and Switzerland in conjunction with anaerobic digestion. Only a fraction of the methane produced in digestion is needed for pasteurization. Approximately 20 to 25 minutes at 70° C is adequate to kill all pathogens.

Liming can be a useful practice for sewage treatment plants producing sludge in excess of their digestion capacity. The excess can be temporarily stabilized for eventual disposal in landfills. Liming to pH 12 reduces the number of bacterial pathogens to a negligible value within one hour. Ascaris ova may survive, but the hazard from parasites is no greater than from digested sludges.

Heat drying of sludges has been used successfully in destroying pathogens and producing a marketable product. Irradiation combined with heat-drying to increase the efficiency of the process is under investigation. Composting is the only method that provides significant pathogen destruction and yields an esthetically acceptable product that can be used beneficially on land as a fertilizer and soil conditioner.

Composting can be an effective means of destroying pathogens, but many variables are involved, including the efficiency of the techniques and the weather.

Sludges that are to be used for fresh food production must be treated by a process that provides at least pasteurization and the sludge should be monitored for those pathogens that are most likely to survive the treatment process. For other uses, the normal die-off rate of pathogens, other processing methods, transport time, and good soil conservation practices should provide adequate protection from the risks due to pathogens. Land receiving less treated sludges should not be converted to food production for at least seven years.

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TOXIC SUBSTANCES

Heavy metals and some organic compounds persist in soil long after they have been applied to land. Unregulated sludge application can lead to phytotoxicity or food-chain risk under some conditions. Application of industrially contaminated sludges at high rates can cause phytotoxicity due to heavy metals such as Zn, Cu, or Ni, or excessive plant uptake and accumulation of Cd and certain organic compounds. The human food chain is protected from excessive levels of most elements except Cd in foods by the "soil-plant barrier." Monitoring of sludge composition, limiting maximum levels of potentially toxic elements and organics in sludges, and regulating cumulative applications of potentially toxic metals and organics, can prevent adverse effects on soil productivity and ensure crop safety.

These potential problems from sludge use must be managed to protect cropland productivity and food safety. They are divided into two groups, temporary and persistent potential problems. The temporary potential problems disappear after the first year or, at most, three years after sludge is applied. They include odor, surface run-off of pathogens, phytotoxicity from excessive soluble salts, too rapid biodegradation of inadequately stabilized sludge, excessive nitrate leaching to groundwater if too much sludge is applied, and if sludge is not treated properly, pathogens. On the other hand, if sludge or compost is used according to the regulations in the United States, none of these should cause impacts.

After these temporary problems are all past (the pathogens die off, etc.), there remain the persistent potential problems, those that have to do with heavy metals, and with persistent organic compounds like the PCB's. These toxic materials have to be considered persistent, because they remain in the soil for a prolonged period, heavy metals may have a half-life of about a thousand years, and polychlorinated biphenyls (PCB's) about a 10-year half-life.

Thus, it can be seen that it is imperative for safe sludge utilization or disposal operations to have detailed information on the sludge characteristics and to monitor its land application. Wastewater treatment plants in the United States are required to routinely analyze their sludges for most of the contaminants of concern.

A. TOXIC ORGANIC COMPOUNDS[4]

Animals can be exposed to toxic organic compounds (TO's) present in wastes by: (1) direct ingestion of wastes, wastes adhering to forages, wastes lying on the soil surface, or soil treated with wastes; (2) ingestion of plant tissues which are increased in TO content after plant uptake or volatilization from the soil to the plant; or (3) consumption of animal products enriched in TO by other routes. The chemical and physical properties of a TO control its adsorption by soil, volatilization, plant uptake and translocation, biodegradation (in soil, plant or animal), and accumulation in animal tissues.

Based on research on bioaccumulation of PCB's, PCB's should not exceed 2.0 mg/kg dry sludge if milk cows are to be allowed to graze pastures under worst-case conditions which allow 14% sludge in their diet. This was based on a bio-magnification from diet to milk fat of 5-fold, and United States Food and Drug Administration (FDA) tolerances of 1.5 mg PCB/kg milk fat. Forages grown on soils containing PCB's have PCB residues about 0.1 that of the soil, or lower during the first crop year. Good management practices (delay grazing for 30 days after surface application of sludge, and supply feed concentrates during periods of low forage availability) reduce sludge ingestion so that 10 ppm PCB's could be allowed in sludge which is to be surface applied at 10 metric tons/ha/yr. Injection of sludge below the soil surface would further reduce exposure.

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[4] From Workshop papers, "Potential Effects of Sludge-Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney; and "Public Health Risk and Risk Assessment in Relation to the Management of Municipal Wastes on Lands," by Elmer W. Akin.

Although research continues to examine the possibilities of problems from toxic organic compounds in sewage sludge, the case has not been made for regulating compounds other than PCB's. Nevertheless, the U.S. Environmental Protection Agency (USEPA) and state regulatory agencies in the United States require periodic monitoring for a list of "priority pollutants" listed in Table 3 and this information should be evaluated for any land application program. Fortunately, for land application purposes, wastewater treatment processes do not concentrate most toxic organics in the sludge since they are either soluble and are not removed from the wastewater or they are volatile and are released to the air during treatment. The small amounts that do occur in sludges are mostly immobilized by adsorption of the surfaces of soil particles where they are decomposed by soil microorganisms.

Table 3

Alphabetical Listing of Section 307(a) TOXIC POLLUTANTS

1. *1.1.1-TRICHLOROETHANE*
2. *1.1.2.2-TETRACHLOROETHANE*
3. *1.1.2-TRICHLOROETHANE*
4. *1.1-DICHLOROETHANE*
5. *1.1-DICHLOROETHYLENE*
6. *1.2.4-TRICHLOROBENZENE*
7. *1.2-DICHLOROETHANE*
8. *1.2-DICHLOROBENZENE*
9. *1.2-DICHLOROPROPANE*
10. *1.2-DIPHENYLHYDRAZINE*
11. *1.2-TRANS-DICHLOROETHYLENE*
12. *1.3-DICHLOROBENZENE*
13. *1.3-DICHLOROPROPANE (CIS AND TRANS ISOMERS)*
14. *1.4-DICHLOROBENZENE*
15. *1-(CHLOROETHOXY) METHANE*
16. *2.3.7.8-TETRACHLORODIBENZO-P-DIOXIN (TCDD)*
17. *2.4.6-TRICHLOROPHENOL*
18. *2.4-DICHLOROPHENOL*
19. *2.4-DIMETHYLPHENOL*
20. *2.4-DINITROPHENOL*
21. *2.4-DINITROTOLUENE*
22. *2.6-DINITROTOLUENE*
23. *2-CHLOROETHYL VINYL ETHER*
24. *2-CHLORONAPHTHALENE*
25. *2-CHLOROPHENOL*
26. *2-NITROPHENOL*
27. *3.3-DICHLOROBENZIDINE*
28. *3.4-BENZOFLUROANTHENE*
29. *4.4-DDD (P.P'-TDE)*
30. *4.4-DDE (P.P'-DDE)*
31. *4.4-DDT*
32. *4.6-DINITRO-2-METHYLPHENOL*
33. *4-BROMOPHENYL PHENYL ETHER*
34. *4-CHLOROPHENYL PHENYL ETHER*
35. *4-CHLORO-3-METHYLPHENOL*
36. *4-NITROPHENOL*
37. *ACENAPHTHENE*

38. ACENAPHTHYLENE
39. ACROLEIN
40. ACRYLONITRILE
41. ALDRIN
42. ANTHRACENE
43. ANTIMONY AND COMPOUNDS
44. ARSENIC AND COMPOUNDS
45. ASBESTOS
46. A-BHC-ALPHA
47. A-ENDOSULFAN-ALPHA
48. BENZENE
49. BENZIDINE
50. BENZO (A) ANTHRANCENE (1.2-BENZANTHRACENE)
51. BENZO (A) PYRENE (3.4-BENZOPYRENE)
52. BENZO (GHI) PERYLENE (1.12-BENZOPERYLENE)
53. BENZO (K) FLUORANTHENE (11.12-BENZOFLUORANTHENE)
54. BERYLLIUM AND COMPOUNDS
55. BIS (2-CHLOROETHYL) ETHER
56. BIS (2-CHLOROISOPROPYL) ETHER
57. BIS (2-ETHYLHEXYL) PHTHALATE
58. BROMOFORM (TRIBROMOMETHANE)
59. BUTYL BENZYL PHTHALATE
60. B-BHC-BETA
61. B-ENDOSULFAN-BETA
62. CADMIUM AND COMPOUNDS
63. CARBON TETRACHLORIDE (TETRACHLOROMETHANE)
64. CHLORDANE (TECHNICAL MIXTURE & METABOLITES)
65. CHLOROBENZENE
66. CHLORODIBROMOMETHANE
67. CHLOROETHANE
68. CHLOROFORM (TRICHLOROMETHANE)
69. CHROMIUM AND COMPOUNDS
70. CHRYSENE
71. COOPER AND COMPOUNDS
72. CYANIDES
73. DEILDRIN
74. DIBENZO (AH) ANTHRACENE (1,2,5,6-DIBENZANTHRACENE)
75. DICHLOROBROMOMETHANE
76. DIETHYL PHTHALATE
77. DIMETHYL PHTHALATE
78. DI-N-BUTYL PHTHALATE
79. DI-N-OCYTL PHTHALATE
80. D-BHC-DELTA
81. ENDOSULFAN SULFATE
82. ENDRIN
83. ENDRIN ALDEHYDE
84. ETHYLBENZENE
85. FLOURANTHENE
86. FLUORENE
87. G-BHC (LINDANE) GAMMA
88. HEPTACHLOR
89. HEPTACHLOR EXPOXIDE
90. HEXACHLOROBENZENE
91. HEXACHLOROBUTADIENE
92. HEXACHLOROCYCLOPENTADIENE

93. *HEXACHLOROETHANE*
94. *INDENO (1,2,3-CD) PYRENE (2,3-0-PHENYLENEPYRENE)*
95. *ISOPHORONE*
96. *LEAD AND COMPOUNDS*
97. *MERCURY AND COMPOUNDS*
98. *METHYL BROMIDE (BROMOMETHANE)*
99. *METHYL CHLORIDE (CHLOROMETHANE)*
100. *METHYLENE CHLORIDE (DICHLOROMETHANE)*
101. *NAPHTHALENE*
102. *NICKEL AND COMPOUNDS*
103. *NITROBENZENE*
104. *N-NITROSODIMETHYLAMINE*
105. *N-NITROSODIPHENYLAMINE*
106. *N-NITROSODI-N-PROPYLAMINE*
107. *PCB-1016 (AROCHLOR 1016)*
108. *PCB-1221 (AROCHLOR 1221)*
109. *PCB-1232 (AROCHLOR 1232)*
110. *PCB-1242 (AROCHLOR 1242)*
111. *PCB-1248 (AROCHLOR 1248)*
112. *PCB-1254 (ABOCHLOR 1254)*
113. *PCB-1260 (AROCHLOR 1260)*
114. *PENTACHLOROPHENOL*
115. *PHENANTHRENE*
116. *PHENOL*
117. *PYRENE*
118. *SELENIUM AND COMPOUNDS*
119. *SILVER AND COMPOUNDS*
120. *TETRACHLOROENTHYLENE*
121. *THALLIUM AND COMPOUNDS*
122. *TOLUENE*
123. *TOXAPHENE*
124. *TRICHLOROETHYLENE*
125. *VINYL CHLORIDE (CHLOROETHYIENE)*
126. *ZINC AND COMPOUNDS*

(Source: United States Environmental Protection Agency).

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B. HEAVY METAL EFFECTS[5]

Phytotoxic Effects

When sludges are mixed into soil, chemical forms of heavy metals present in the sludge may be modified and heavy metal availability to plants is controlled by the equilibrium processes of the amended soil. Metals and persistent organics are chelated or adsorbed to soil constituents (organic matter, hydrous oxides of Fe, Mn, etc., clays) so that only very small amounts of the added metals remain soluble in the water phase of soil, and the soil solution. Most of the soluble Zn, Cu, etc., in soil solution is present as chelates with low molecular weight organic molecules, such as fulvic acid; and free metal ion activity is very low. Soil pH strongly affects each of these chelation, adsorption, or precipitation processes in soil; metal cation levels in the soil solution are reduced, and metal anion levels are increased as pH increases. Metals in soil solution can move from the solid phases of soil to the roots and be absorbed by the plant. Soluble salts or organic chelators increase metal movement to the roots and uptake by plants.

When plants absorb excessive amounts of heavy metals, the plant can be injured and its growth reduced. Severe phytotoxicity can kill a plant or allow normal environmental stresses on plants to kill the plant. Of the elements commonly found in organic wastes, only Zn, Cu, Ni, and Mn are likely to cause phytotoxicity with improper management of sludge use. Because soil pH affects sorption of these metals by soil so strongly, soil pH has a dominant effect on potential for phytotoxicity. Further, natural soil Mn can become more plant available due to sludge use, and Zn plus Mn phytotoxicity result; this process is especially pH dependent. Excess Cu and Ni cause injury of the plant's roots, and Cu and Ni toxicity is generally expressed as yellow (chlorotic) young leaves which is Cu-or Ni-induced Fe-deficiency. Zn and Mn are translocated more freely to the leaves; although Zn and Mn can injure roots and induce chlorosis, their toxicity is usually manifested through injury of older leaves and reduction of plant growth through interferences with biological processes. Boron toxicity has resulted when sensitive crops are grown on soils amended with high rates of refuse compost. A summary of responses of different crops to sludge applied metals is shown in Table 4. Most vegetable crops and legumes were relatively sensitive to metals in acidic soils.

The United States Department of Agriculture (USDA) has provided recommendations for maximum cumulative applications of Zn, Cu, and Ni such that phytotoxicity will occur only under conditions of poor pH managament and be fully corrected under pH conditions ($\geq$6.2) which are normal good agricultural management practices. Table 5 shows those recommendations.

Although phytotoxicity can result from these recommendations (sensitive crops, pH$<$5.5), phytotoxicity can cause the landowner to add limestone; the landowner is made aware of his mismanagement by the natural process of phytotoxicity. This, in turn, prevents high plant levels of Cd and other metals because visibly sick crops are substantially reduced in yield. This role of phytotoxicity will be discussed more in the food-chain section.

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[5] From Workshop paper, "Potential Effects of Sludge-Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney.

Table 4

Relative Sensitivity of Crops to Sludge-Applied Heavy Metal

Very Sensitive[1]	Sensitive[2]	Tolerant[3]	Very Tolerant[4]
chard	mustard	cauliflower	corn
lettuce	kale	cucumber	sudangrass
redbeet	spinach	zucchini squash	smooth bromegrass
carrot	brocolli	fescue	'Merlin' red
turnip	radish	flatpea	
peanut	tomato		
	marigold	oat	
ladino clover		orchardgrass	
alsike clover	zigzag, Red Kura and crimson clover	Japanese bromegrass	
crownvetch	alfalfa	Switchgrass	
'Arc' alfalfa	Korean lespedeza	Red top	
white sweetclover	Sericea lespedeza	Buffelgrass	
yellow sweetclover	Blue lupin	Tall fescue	
	Birdsfoot prefoil	Red fescue	
weeping lovegrass	Hairy vetch	Kentucky bluegrass	
Lehman lovegrass	Soybean		
Deertongue	Sanpbean Timothy		
	Colonial bentgrass		
	Perennial ryegrass		
	Creeping bentgrass		

[1] Injured at 10% of a high metal sludge at pH 6.5 and at pH 5.5.

[2] Injured at 10% of a high metal sludge at pH 5.5, but not at pH 6.5.

[3] Injured at 25% high metal sludge at pH 5.5, but not at pH 6.5, and not at 10% sludge at pH 5.5 or 6.5.

[4] Not injured even at 25% of a high metal sludge, pH 5.5.

(Source: Workshop paper, "Potential Effects of Sludge-Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney).

Table 5

Recommended Maximum Cumulative Sludge Applications for Privately-Owned Cropland

Metal	Soil Cation Exchange Capacity 0-5	5-15	>15 meg/100g
	Maximum Application, kg/ha		
Zn	250	500	1000
Cu	125	250	500
Ni	50	100	200
Cd	5	10	20
Pb	500	1000	2000

1. Annual Cd application should not exceed 2 kg/ha from dewatered or composted sludge, or 1 kg/ha from liquid sludge; sludge should not supply more crop available nitrogen than the crop requires.
2. Sludges with Cd $>$ 25 ppm should not be applied unless the Cd/Zn $<$ 0.015; if Cd/Zn exceeds 0.015, an abatement program to reduce sludge Cd should be initiated.
3. These recommendations apply only to soils that are adjusted to pH $>$ 6.5 when sludge is applied and are to be managed to pH $\geq$ 6.2 thereafter.
4. Leafy vegetables or tobacco cropland should not receive sewage sludge application.
5. The cation exchange capacity is for unamended soil.

(Source: Workshop paper, "Potential Effects of Sludge-Borne Heavy Metals and Toxic Organics on Soils, Plants and Animals, and Related Regulatory Guidelines," by Rufus L. Chaney).

Sludges apply not only potentially phytotoxic metals, but also other materials (e.g., organic matter and phosphate) which counteract phytotoxicity. Mixtures of metals may not be as toxic as individual metals due to interactions. Phytotoxicity has not be observed resulting from use or the very good low metal sludges and composts that are characteristic of the Washington, D.C. metropolitan area. There appears to be a relationship between potential for phytotoxicity and absolute level of metals in sludge. It seems clear that potential for metal phytotoxicity problems is greater with high metal sludges and that application of high metal sludges to private cropland should be discouraged by governmental regulations.

Each element has its unique chemical and physical characteristics in waste-soil-plant systems. If the compounds of an element are essentially insoluble at practical soil pH levels (5.5-8), then that element has a very low concentration in the soil solution and cannot be absorbed at an appreciable rate. If an element is adsorbed or chelated very strongly by the soil, even though it is not precipitated, it similarly has low uptake. If an element is weakly adsorbed, and not precipitated, then the element is subject to plant uptake or leaching through the soil.

Soil Interactions

As noted above, soils adsorb and/or chelate many microelements. Adsorption occurs on hydrous oxides of Mn and Fe, clays, organic matter, and other soil minerals. Organic matter can chelate microelements. Adsorption, chelation, and dissolution of precipitated mineral forms of an element, are all pH-dependent. Cations are weakly bound at lower pH, strongly bound at high pH. Selenite and molybdate (anions) are more strongly sorbed at low pH than at high pH. Boron forms soluble H_3BO_3 at low pH and greater plant uptake occurs at low pH.

The pH of the soil immediately adjacent to plant roots (the rhizo-cylinder) is important in plant uptake of metals. Uptake occurs after movement (diffusion) of the metal from the soil particles to the root surface. When roots absorb NH_4, the pH of the rhizocylinder soil declines, and when the roots absorb NO_3, the pH rises. The form of N absorbed by the root has a strong influence on metal uptake. Most crop N is absorbed as NO_3-N which raises rhizosphere pH. Use of NH_4-fertilizers also causes the bulk of soil to decline since H+ is generated when NH_4 is oxidized to NO_3. Application of limestone corrects soil acidity. Applying excessive limestone minimizes metal cation uptake, but promotes uptake of anions (Mo, Se).

Soil pH and organic matter are the soil factors most important in plant uptake of microelements. Other factors which influence uptake are soil temperature, soluble salts, added soluble chelators, soil moisture status, and fertility.

When sludges supply metals, the uptake depends on the period since application. The rapid breakdown of organic matter (especially at higher sludge rates) supplies organic ligands and NH_4-N, both of which facilitate metal diffusion and uptake. Radish absorbed very high levels of Cu and Zn and suffered phytotocicity when grown on freshly amended heated (37°C) soils; five crop years later, soil temperature had almost no effect on uptake, and healthy crops resulted (Table 6). The higher soluble salts in pot studies or high rates of recent sludge additions can increase soluble metals by forming complexes (Cl) or ion pairs (SO_4) with metals, theraby increasing metal diffusion and uptake.

Table 6

Effect of Soil Temperature and Time After Sludge Application Effect on Metal Concentration in Radish Leaves

Sludge Rate Mt/ha	Soil pH	First Crop Year Metals in Radish Leaves			Soil pH	Sixth Crop Year Metals in Radish Leaves		
		Zn	Cu	Cd		Zn	Cu	Cd
		mg/kg dry				mg/kg dry		
				Ambient (22°C)				
0	5.3	63e(*)	9.8cf	1.0a	6.7	35e	5.1e	0.8ab
56	6.0	295de	16.6de	1.1a	6.5	95cd	7.6cd	0.6b
112	6.2	663bc	36.1b	1.8a	6.1	152b	9.0c	1.0a
				Heated (35°C)				
0	5.6	86e	6.8f	2.1a	6.7	27e	4.3e	0.5b
56	6.0	490cd	26.9c	2.8a	6.5	51e	6.9d	0.5b
112	5.9	1070a	59.9a	2.6a	6.3	108cd	10.7b	0.8ab

(*) Means followed by the same letter in the same column are not significantly different from each other ($p=0.05$).

Food-Chain Effects

Liquid sludges can be spray-applied to cropland and tilled into the soil. Alternatively, liquid sludge can be sprayed onto forage or pasture land where it can contact plants and/or remain on the soil surface. Dewatered or dried sludges or composted wastes can be applied and mixed with or remain on the soil surface. These management options allow substantially different quantities of waste-borne toxic chemicals to enter the food chain by quite different routes. Some options allow animals to directly ingest sludges, while other options use reactions in soils and properties of plants to largely prevent exposure. When liquid sludges (≤10% solids) are sprayed on pastures or forage crops, a thin film of the sludge coats the plant foliage. Research has found that some wastes dry and adhere strongly while others dry and flake off upon weathering.

Soil ingestion can also expose humans to waste-applied microelements in land treatment sites subsequently developed for housing. Some children and adults deliberately consume soil in a practice called "pica." If the soil is high in Pb (over 500-1000 ppm), individuals may absorb excessive amounts of Pb. Children also ingest soil and dust due to hand-to-mouth play activities and by mouthing toys, etc.

Soil or sludge ingestion can be an important process which allows entry of a sludge-borne microelement or toxic organic into the food-chain especially when the element is normally not absorbed by plants. For some elements (Zn, Cd, Mn, Se, etc.), plant levels often exceed soil levels, and plant uptake is a more important process than soil ingestion. However, soil ingestion is a potential route for allowing excessive Pb, Fe, Cu, F, As, Hg, Cu, Co, Mo, Se, and other elements into the food-chain. Further, soil ingestion can interfere with availability to animals of microelements in plants.

Research has shown that by applying sludge to recently mowed fields, waiting to allow the crop to grow and dilute the adhering sludge keeps the sludge content of forages below 3-5%. These practices coupled with use of sludges low in toxic materials protects the health of livestock and safety of animal food products. Subsurface injection of sludge removes this food-chain pathway for sludge-borne toxic materials. Some elements are easily absorbed and translocated to food-chain plant tissues (e.g., Zn, Cd, Mn, Mo, Se, B), while others are not. These other elements are strongly bound to soil or retained in plant roots, and are not translocated to plant foliage in injurious amounts, even when soils are greatly enriched (e.g., Fe, Pb, Hg, Al, Ti, Cr3+, Ag, Au, Sn, Si, Zr). Even though an element may be easily or relatively easily absorbed and translocated to plant foliage, phytotoxicity may limit plant levels of these elements to levels safe for animals (e.g., Zn, Cu, Ni, Mn, As, B).

Soil-Plant Barrier

A "soil-plant barrier" protects the food chain from toxicity of a microelement whenever one or more of the following processes limit maximum levels of that element in edible plant tissues to levels safe for animals: (1) insolubility of the element in soil prevents uptake; (2) immobility of an element in fibrous roots prevents translocation to edible plant tissues; or (3) phytotoxicity of the element occurs at concentrations of the element in edible plant tissues below that injurious to animals.

Unfortunately, the "soil-plant barrier" does not protect animals from toxicities of all elements. The exceptions important in assessing risk from land application of municipal sludge are Cd, Se, and Mo; a few more elements may have to be considered for land application of industrial wastes (Be, Co). Ingestion of amended soil or sludge can circumvent the "soil-plant barrier." Many elements are so insoluble or non-toxic that animal health is not influenced even if ingested soil or waste contains the element (e.g., Cr3+, Zr, Ti, Al, Sn, Si). However, direct ingestion of soil or wastes rich in some elements (e.g., Cu, F, Zn, Pb, Fe2+, As, Co, and Hg) allows risk to livestock when risk would have been significant if the sludge were mixed with the surface soil (0-15cm).

Evaluation of the potential impact of microelements on animals via their consumption of sludge, sludge-amended soils or crops grown on sludge-amended soil is very complex. Animal species differ in tolerance of microelements. Tolerance to microelements is also influenced by age; younger animals are generally more sensitive than older. Crop species absorb unequal amounts of microelements. Total and relative microelement uptake is affected by crop species and cultivar, soil pH, organic matter, soil temperature and other factors. Wastes differ in levels of elements and ratios among elements. Individual potentially toxic elements interact with other elements in the diet, often reciprocally. These interactions are often the basis for physiological toxicity; hence, interactions are of great importance in assessing risk.

Interactions affecting Cu deficiency in ruminant animals were among the first studied, and have been intensely examined because of their practical significance. Animals can experience simple Cu deficiency or Mo-induced, sulfate-induced, or Zn-, Cd-, or Fe-induced deficiency.

In most cases, food-chain toxicity is a result of microelement imbalance as much as it is a result of increased supply of one potentially toxic element. When one element is so increased that the ratio of it to other elements or dietary constituents is great enough to induce a deficiency of another, then animal weight gain declines and a health effect is observed. Consumption of sludge or sludge-amended soil is a very different case for risk assessment than standard toxicological studies where a soluble salt of one element is added at rates to cause health effects (and often to purified rather than practical diets). With sludge ingestion increased levels of dietary Zn are balanced by increased levels of Cu and Fe. Recently, research on potential toxicity from ingestion of high Cu swine manure had led to the conclusion that interactions can reverse toxicity predicted from "toxicology" studies.

Cadmium Uptake

Cadmium is not essential for plants. Although one study indicated Cd was essential for rats, it is not generally agreed that Cd is essential for animals.

It now appears that Cd activity in most soils is controlled by adsorption rather than by formation of crystalline inorganic compounds. $CdCo3$ can form in low cation exchange capacity, low organic matter, calcareous soils. Under anaerobic conditions, CdS forms in soil; CdS has very low solubility and is unavailable to plants, but is readily oxidized in aerobic soil. Unfortunately, formation of CdS is not a practical management practice to minimize Cd uptake for crops other than rice.

Of all soil properties affecting Cd level in plants, soil pH has the greatest effect. Increasing soil pH causes stronger adsorption of Cd by soil and reduces Cd uptake. Of other soil chemical properties, soil organic matter has been shown to have some effect; since higher organic matter reduces Cd uptake. Other soil factors which affect Cd uptake include: temperature, soluble salts, chelators, and water status.

Crops differ remarkably in their Cd accumulation, Cd tolerance, and translocation of Cd to edible plant parts. Tobacco, lettuce, spinach, chard, endive, cress, and turnip accumulate much higher foliar Cd levels than other leafy crops (e.g., kale, collards, cabbage). Although Cd in edible root of radish, turnip and beet is only a small fraction of the Cd level in the shoots of the plants, carrot root Cd is about half of carrot leaf Cd. Similarly, the ratio (Cd in grain): (Cd in leaf) ranges from very low for corn to relatively high for wheat, oat, and soybean; this ratio in soybean was reduced from > 1 to < 0.2 by increasing soil Zn. The important conclusion is that the phytotoxicity of Cd does not limit crop Cd to acceptable levels.

Cadmium Health Effects

Cadmium is an unusual and difficult case for evaluation of risk to the food-chain. In contrast to other elements, Cd has a quite long biological half-life in humans generally considered 20 years. Absorbed Cd is bound to a low molecular weight protein to form metallothionein which is accumulated and retained in the kidney for a long period. High metallothionein-Cd in the kidney can lead to adverse health effects in this organ.

Over one's lifetime, *chronic* food chain Cd exposure can cause different health problems than those experienced from *acute* exposure. Long-lived animals (e.g., humans) are at greater risk of this health effect than are short-lived animals (wildlife; domestic animals). Accumulation of Cd in organ meats (liver, kidney) was the basis for suggesting a low dietary Cd tolerance in domestic animals rather than a direct health effect to the animals.

The name "itai-itai" disease (translated as ouch-ouch disease) came from expressions of pain by elderly women suffering repeated bone fractures due to Cd-induced osteomalacia. Although the osteomalacia brought attention to this environmental Cd disease, severe osteomalacia does not frequently result in humans ingesting excessive Cd. Renal proximal tubular dysfunction (Fanconi syndrome) is the first health effect of excessive chronic Cd exposure. The renal disease had high incidence in areas where Cd exposure was substantially increased, and showed a dose-response relationship with Cd exposure (expressed as "Cd level in rice-times-years ingested"). All individuals with advanced itai-itai disease had severe proteinuria characteristic of the kidney disease. Renal disease subsequently proceeded to osteomalacia in some workers who ceased exposure when the kidney disease was identified. However, this aspect of Cd disease is poorly understood.

Renal tubular dysfunction (Fanconi syndrome) resulting from Cd ingestion is quite different from classic kidney failure. Fanconi syndrome seldom proceeds to kidney failure requiring dialysis. Fanconi syndrome (low molecular weight proteinuria, glucosuria, aminoaciduria, phosphaturia, etc.) is the first Cd health effect; if Cd-exposure (rate-times-duration) is increased, kidney stones and osteomalacia/osteoporosis may result. Neither hypertension nor prostate cancer incidence are increased even when proteinuria is severe. Although laboratory studies with rats and other animals have shown that anemia, enteropathy, and teratogenesis (due to Cd-induced Zn or Cu deficiency in the fetus) can result from ingested Cd, these are very unlikely with practical diets.

Cadmium absorption by animals is strongly influenced by other dietary factors. Iron status of the animal appears to be the most important control of percent-absorption of Cd. Zinc status of the animal and dietary Zn level is the next most important factor, followed by dietary Ca. Protein and fiber in the diet and age of animal also influence Cd retention. These factors should allow a greater percent-absorption rate for women than men. Women as a group showed greater Cd absorption, and women's kidney Cd exceeds men's in autopsy kidney studies, as did women's suceptibility to excessive dietary Cd in Japan.

Dietary interactions can, thus, influence bioavailability of Cd. Leafy and root vegetables which are enriched in Cd may also be a good dietary supply of Zn, Fe, and Ca. Leafy vegetables have been shown to provide bioavailable Fe and Zn. Consuming sufficient garden food Cd to pose a risk to *suceptible* individuals would result in increased dietary Fe, Zn, and Ca, thereby shifting the individuals to a less suceptible population group; i.e., these two groups may be mutually exclusive.

Feeding studies have been conducted both with sludge, and with crops grown on sludge-fertilized soil. Ingestion of sludge Cd has been evaluated in ruminant and monogastric animals with meat work done with cattle. When sludges with high Cd and high Cd: Zn were fed, kidney Cd was significantly increased. However, when sludges with lower Cd and low Cd:Zn were fed, kidney Cd was not significantly increased. Sludge Cd was less bioavailable to swine than equal dietary Cd added as CdCl. Food products of animals are unchanged in Cd except for liver and kidney.

Tobacco is an especially high risk crop in terms of potential for Cd effects on humans. Among all crops studied to date, tobacco accumulates more Cd per unit soil Cd than any other. Tobacco is normally grown on strongly acid soils to prevent crop loss from root diseases. This soil pH management leads to maximum Cd uptake under normal crop production conditions. In contrast, most other crops are best grown at pH 6.5 to 7. Tobacco is normally high in Cd compared to leaves of other crop plants. When tobacco is grown on sewage sludge-amended soils, crop Cd level can be increased from one to as high as 44 ppm Cd in dry leaves with only one ppm soil Cd.

Cadmium in tobacco is an important source of Cd for humans. Individuals who smoke one pack of cigarettes per day have about 50% higher Cd in kidney cortex than non-smokers. About 15% of cigarette Cd enters the mainstream smoke. Filters can remove much of this Cd and reduce Cd exposure of smokers. Based on the potential of sludge-applied Cd to increase risk of chronic kidney disease in smokers if sludge were applied to tobacco cropland, US-EPA (1979a) regulated and discouraged this practice.

In summary, the "soil-plant barrier" does not protect the food-chain from excessive Cd. Unregulated applications of Cd-bearing wastes can cause health effects in humans. Cadmium is not easily kept out of food crops; conversion of treated land to gardens is a worst-case scenario upon which regulations to limit Cd applications were based. Recent research on gardens polluted with Cd by mining wastes or smelter emissions support the view that gardens can provide much Cd in locally grown foods to the family maintaining the garden for many years.

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POTENTIAL BENEFITS FROM LAND APPLICATION OF SLUDGE[6]

General

There are benefits and risks associated with use of sludge. Sludge can supply macronutrients like nitrogen phosphorus and potassium. Sludge is also a good microelement fertilizer; zinc, copper, and iron can correct deficiencies of those elements in soils and can be very beneficial. Sludge adds organics matter which acts as a soil conditioner; this improves soil physical properties and water-holding capacity. However, sludge-amended soils have to be cropped to utilize the applied nitrogen so that nitrate does not leach into the groundwater in excessive amounts. As long as sludges are applied at a rate that does not apply more nitrogen than the crop's need, sludge nitrogen is not really any different as far as the potential for contaminating groundwater with nitrate than is routine use of chemical fertilizers.

Sewage sludge can be used beneficially on agricultural land as a source of plant nutrients and as a conditioner or organic amendment to improve soil tilth. Some sludges may also contain lime, often required in certain regions for proper management of soil acidity. Reliable information on the nutrient level of the sludge is needed for optimum utilization. Sludges that contain excessive levels of heavy metals, salts, organic chemicals, or pathogens, however, may be unsuitable for land application because of possible adverse effects on the environment and human health, as well as on crop quality and yield.

Land application projects are based on the concept that the sludges will supply plant nutrients/fertilizers. For a project to be worthwhile, it is essential that the potentially toxic heavy metals be in sufficiently low concentrations in the sludge that a useful amount of fertilizer can be applied without risking toxic effects. Thus, for regulatory purposes, maximum allowable concentrations of heavy metals in the sludge are based on applications of the sludge to the same land over a number of years. Different countries have based their regulations on varying assumptions, resulting in a range of acceptable values as seen in Table 7.

Fertilizer Value

Placing a monetary value on sludge is difficult. Its ultimate value will depend upon the extent to which it can substitute for commercial fertilizers, on the value of the crop or commodity produced, and on the physical and chemical characteristics of the sludge. The total value is influenced by the rate of application, the physical and chemical characteristics of the sludge, its esthetic characteristics, costs of fertilizers and other organic amendments, the value of the final agricultural product, and the governmental constraints put on its use. The net monetary value of sludge in agriculture is determined by the market value of crops or commodities produced through its use less the costs of processing, transporting, and applying to land.

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[6] By George B. Willson.

Table 7

Maximum Permissible Heavy Metal Concentrations (mg/kg dry wt.) in Sludges Considered to be Acceptable for use on Agricultural Lands

Element	Belgium	Canada	Denmark	Finland	France	Germany	Netherlands	Norway	Sweden	Switzerland	All Countries Panne	All Countries Meridian	CEC R	CEC M
As	10	75					10				10-75	10		
Cd	10	20	8	30	20	20	10	10	15	30	8-30	7	20	40
Co	20	150		100				20	50	100	20-150	75		
Cr	500			1000	1000	1200	500	200	1000	1000	200-1200	1000	750	
Cu	500			3000	1000	1200	600	1500	3000	1000	500-3000	1100	1000	1500
Hg	10	5	6	25	10	25	10	7	8	10	5-25	10	16	
Mn	500			3000				500			500-3000	500		
Mo		20								20				
Ni	100	180	30	500	200	200	100	100	500	200	30-500	200	300	40
Pb	300	500	400	1200	800	1200	500	300	300	1000	300-1200	500	750	100
Se	25	14			100						14-100	25		
Zn	2000	1050		5000	3000	3000	2000	3000	10000	1000	1000-10000	3000	2500	300

Canada - Values apply to sludge and sludge-based products containing <5% nitrogen.
CEC - Commission of the European Communities, Directive. - Recommended (R) maximum and Mandatory (M), not to be exceeded concentrations.
United Kingdom - Sludge for public distribution should not contain more than 20 mg Cd/kg dry wt. Sludges applied to pasture land should not contain more than 3500 mg F/kg dry wt. and applied to pasture land, gardens and recreational areas should not contain more than 2000 mg Pb/kg dry wt.
United States - Sludge applied to fruit and vegetable crop land should not contain more than Cd, 25; Pb, 1000; and polychlorinated biphenyls (PCB's), 10 mg/kg dry wt.

(Source: M.D. Webber, Canada: A. Kloke, Germany; J. Chr. Tjell, Denmark. Third International Symposium, 1983. Commission of the European Countries, Brussels.)

The value of the sludge is positively related to the price of substitute products, such as chemical fertilizers, lime, or other soil conditions. As the price of these items increases, the value of sludge also increases.

Generally, the rate at which sludge is applied is inversely related to its price. As more sludge is applied, crop response follows the general law of diminishing returns. This is apparent through observations of yield increases after additional nutrients and organic matter have been added.

A rigorous economic analysis would relate the value of sludge to all of the above mentioned determinants. No such study has yet been done. Generally, the value of sludge is approximated by multiplying the available nutrients by their price when sold in chemical fertilizers.

Soil Conditioning Effect

The value of sewage sludge organic matter for the improvement of soil tilth is difficult to evaluate and highly dependent upon existing condition of the soil. When sludge is applied to agricultural land, the rates of application should be low in order to minimize potential environmental hazards associated with excess nitrogen or sludge-borne heavy metals. For example, if sludge is applied at a rate equivalent to the nitrogen requirement of agronomic crops, the annual application rate will range between 7 and 23 dry mt/hectare. If sludge is utilized to supply only plant phosphorus needs, the rates of application will be 2-9 mt/hectare. This latter rate may be advantageous in comparison with the high cost of fertilizer P, the relatively high P content of sludge, the greater flexibility in scheduling sludge applications on land at lower rates, and the reduced accumulation of heavy metals in soils at these lower sludge application rates. Its value for improving soil tilth at these rates, however, would be minimal.

The application of sludges and sludge composts alone, at rates equivalent to at least the N requirement of the crop, to marginal agricultural soils often produces significantly higher yields than where commercial fertilizers are applied alone at the same level of N. This is thought to be the result of improved soil physical properties brought about by the application of sludge or sludge compost. Maximum crop response to inorganic fertilizers is dependent upon favorable soil physical conditions. The addition of sludges and sludge composts to soils is known to improve the soil's physical condition by: (a) increasing the water-holding capacity, (b) enhancing aggregation, (c) increasing aeration, (d) improving permeability, (e) increasing water infiltration, and (f) decreasing surface crusting. Addition of sludges and their composts to sandy soils will increase their ability to retain water and render them less droughty. In heavy-textured, clayey soils, the added organic matter will increase permeability to water and air and increase the rate of infiltration of water into the soil and thereby minimize runoff. In turn, these soils will have a greater capacity to store water for plants. Addition of sludge compost to clay soils has also been shown to reduce compaction and increase the rooting depth.

Non-Food Crop Uses

Sludges and their composts can be used to great advantage in the commercial production and establishment of turf grasses and commercial nurseries producing trees and ornamental plants. Large amounts of sludge and sludge composts are used on golf courses, and for landscaping the grounds of public buildings.

In addition to the above uses, sludge products have a major potential for use in the revegetation and reclamation of lands disturbed by erosion, surface mining, by removal of topsoil, and by excavation of gravel deposits. Stripmined lands are among the most hostile of all environments for the establishment and growth of plants because of: (a) extreme acidity (pH is below 3.0 in many places), (b) extreme droughtiness from lack of organic matter and clay, (c) high surface temperatures, (d) lack of nutrients, and (e) very poor physical conditions. Research has shown that the proper use of sewage sludge of stripmined land makes possible the growing of a wide variety of agronomic and horticultural crops, as well as many forages. With proper management, such disturbed lands can be reclaimed in a surprisingly short time and restored to a high level of production.

Estimates of the organic value of sludge also can be derived from the market value of other soil conditioners or topsoil. Sludge products have also been used to replace peat moss in potting mixes.

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LAWS AND REGULATIONS

Developing Countries' Laws

Laws in developing countries specifically governing the utilization of sewage sludges or derived products are practically nonexistent. However, Mexico has a new "General Law on Ecological Equilibrium and Environmental Protection" (1988), which prohibits disposal of hazardous materials and wastes, but may allow treatment and/or utilization subject to criteria in their laws and regulations. Other countries may also have or be drafting laws.

United States Laws Applicable to Land Application of Sewage Sludge

Many U.S. laws affect sewage sludge management practices. Among others, these include the Clean Air Act (CAA) regarding incinerator emissions requirements, the Toxic Substances Control Act (control of the production and disposal of PCBs and other toxic substances), the Safe Drinking Water Act (drinking water quality standards/groundwater protection), the National Environmental Protection Act (environmental impact statements and reviews of major projects), the Federal Food, Drug and Cosmetic Act (filth and contamination of food products, etc.). Provisions of two major U.S. laws directly address the use and disposal of sewage sludge by land application. Section 405 of the Clean Water Act (CWA) directs the Administrator of EPA to issue regulations containing guidelines for all sewage sludge uses and disposal practices. These guidelines are to serve as minimum requirements by operational facilities. The Resource Conservation Recovery Act (RCRA) regulates the disposal, discharge, deposit injection, dumping, spilling, leaking, or placing of solid waste by definition. Under Subtitle D of RCRA "open dumping" of solid wastes, which includes sludges from pollution control facilities as a solid waste is prohibited and the Administrator of EPA is required to issue criteria which define acceptable solid waste disposal practices. Under Subtitle C of RCRA, the development of a comprehensive federal regulatory manifest system is required to control the generation, storage, transport, and disposal of "hazardous" solid wastes. Sewage sludges are not included in the lists of hazardous waste categories contained in the regulations issued by EPA under the authority of Subtitle C of RCRA. However, procedures have been issued to be used for testing any unlisted wastes that may be suspected to exhibit the characteristics of hazardous wastes and to determine if the generation, storage, transport, and disposal of such unlisted wastes must be controlled under the federal hazardous waste regulatory program. The great majority of municipal sludges which have been tested have not been classified as hazardous.

The sewage sludge provisions of the 1987 amendments to the Clean Water Act (the Water Quality Act of 1987 or PL 100-4) require EPA to undertake a number of activities, including the following:

- identification and regulation of toxic pollutants of concern present in sewage sludge; establishing numerical limits and specifying acceptable management practices (or other alternative standards where necessary) for sewage sludge containing such pollutants;
- requiring compliance with the new management practices and numerical limits no later than one year after their publication (or two years if construction is required);
- prior to promulgation of new regulations, impose conditions by issuing permits or take other measures as deemed appropriate to protect public health and the environment; and
- include requirements implementing the new regulations in permits issued publicly owned treatment works, or any other treatment works treating domestic sewage unless such requirements have been included in a permit issued under appropriate provisions of CWA, RCRA, SDWA, MPRSA, CAA, or under State permit programs approved by the Administrator;
- issue procedures for approval of State Programs within a fixed time frame.

In addition, the new CWA amendments contain the following provisions:

- makes it unlawful for any person to dispose of sludge from any treatment works treating domestic sewage for any use except in accordance with the new regulations; and
- lists a specific Section under other sections of CWA for purposes of authorizing inspections, monitoring, entry and reporting requirements, judiciary review, criminal sanctions against willful or negligent violation of the Section requirements.

New technical regulations covering incineration, ocean disposal, landfill, land application, and distribution and marketing practices providing numerical limits for a number of specific chemicals, as well as management practice requirements are being developed by the Office of Water Regulations and Standards.

ANNEX 1

GLOSSARY

The following definitions of terms related to sludge are those used by the Joint Editorial Board representing the American Public Health Association, the American Society of Civil Engineers, The American Water Works Association, and the Water Pollution Control Federation:

- *Dewatering* — The process of partially removing water; may refer to removal of water from a basin, tank, reservoir, or other storage unit, or to separation of water from solid material.
- *Dewatered Sludge* — The solid residue remaining after removal of water from a wet sludge by draining or filtering. Dewatering is distinguished from thickening in that dewatered sludge may be transported by solids handling procedures.
- *Digested Sludge* — Sludge digested under either aerobic or anaerobic conditions until the volatile content has been reduced to the point at which the solids are relatively nonputrescible and inoffensive.
- *Primary Settling Tank* — The first settling tank for the removal of settleable solids through which wastewater is passed in a treatment works.
- *Primary Sludge* — Sludge obtained from a primary settling tank.
- *Primary Treatment* — (1) The first major treatment in a wastewater treatment facility, usually sedimentation but not biological oxidation; (2) the removal of a substantial amount of suspended matter, but little or no collodial and dissolved matter; and (3) wastewater treatment processes usually consisting of clarification with or without chemical treatment to accomplish solid-liquid separation.
- *Primary Wastewater Treatment* — Also called preliminary wastewater treatment. Unit processes consisting of one or more of the following physical and/or chemical operations: screening, comminution and grinding, grit removal, skimming, preaeration, flocculation, sedimentation, flotation, precipitation, sludge pumping, and disinfection. Commonly applied to treatment that consists chiefly of clarification followed by removal treatment, and disposal of sludge.
- *Sedimentation* — The process of subsidence and decomposition of suspended matter carried by water, wastewater, or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called settling. May be enhanced by coagulation and flocculation; and solid-liquid separation resulting from the application of an external force, usually settling in a clarifier under the force of gravity. It can be variously classed as discrete, flocculent, hindered, and zone sedimentation.,
- *Sludge* — (1) The accumulated solids separated from liquids, such as water or wastewater during processing; (2) organic deposits on bottoms streams or other bodies of water; (3) the removed material resulting from chemical treatment, coagulation, flocculation, sedimentation, flotation, and/or biological oxidation of water or wastewater; and (4) any solid material containing large amounts of entrained water collected during water or wastewater treatment.
- *Sludge Cake* — Wastewater solids that have been sufficiently dewatered to form a semisolid mass.

- *Sludge Conditioning* — Treatment of liquid sludge before dewatering to facilitate dewatering and enhance drainability usually by the addition of chemicals.

- *Sludge Dewatering* — The process of removing a part of the water in sludge by any method, such as draining, evaporation, pressing, vacuum filtration, centrifuging, exhausting, passing between rollers, acid flotation, or dissolved air flotation, with or without heat. It involves reducing from a liquid to a spadable condition rather than merely changing the density of the liquid (concentration) on the one hand or drying (as a kiln) on the other.

- *Sludge Digester* — A tank in which sludge is placed for the purpose of permitting digestion to occur. See also Sludge Digestion.

- *Sludge Digestion* — The process by which organic or volatile matter in sludge is gasified, liquified, mineralized, or converted into more stable organic matter through the activities of either anaerobic or aerobic organisms.

- *Sludge Drying* — The process of removing a large percentage of moisture from sludge by drainage or evaporation by any method.

- *Sludge Excess* — The sludge produced during recirculation in an activated sludge treatmant plant that is not needed to maintain the process and not returned to the aeration tank, but is withdrawn from circulation

- *Sludge Filter* — A device in which wet sludge, usually conditioned by a coagulant is partly dewatered by means of vacuum or pressure.

- *Sludge Thickening* — The increase in solids concentration of sludge in a sedimentation or digestion tank.

- *Sludge Treatment* — The processing of wastewater sludges to render them innocuous. This may be done by aerobic or anaerobic digestion followed by drying on sand beds, filtering and incineration, filtering and drying, or wet air oxidation.

- *Undigested Sludge* — Settled sludge promptly removed from sedimentation tanks before decomposition has much advanced. Also called raw sludge.