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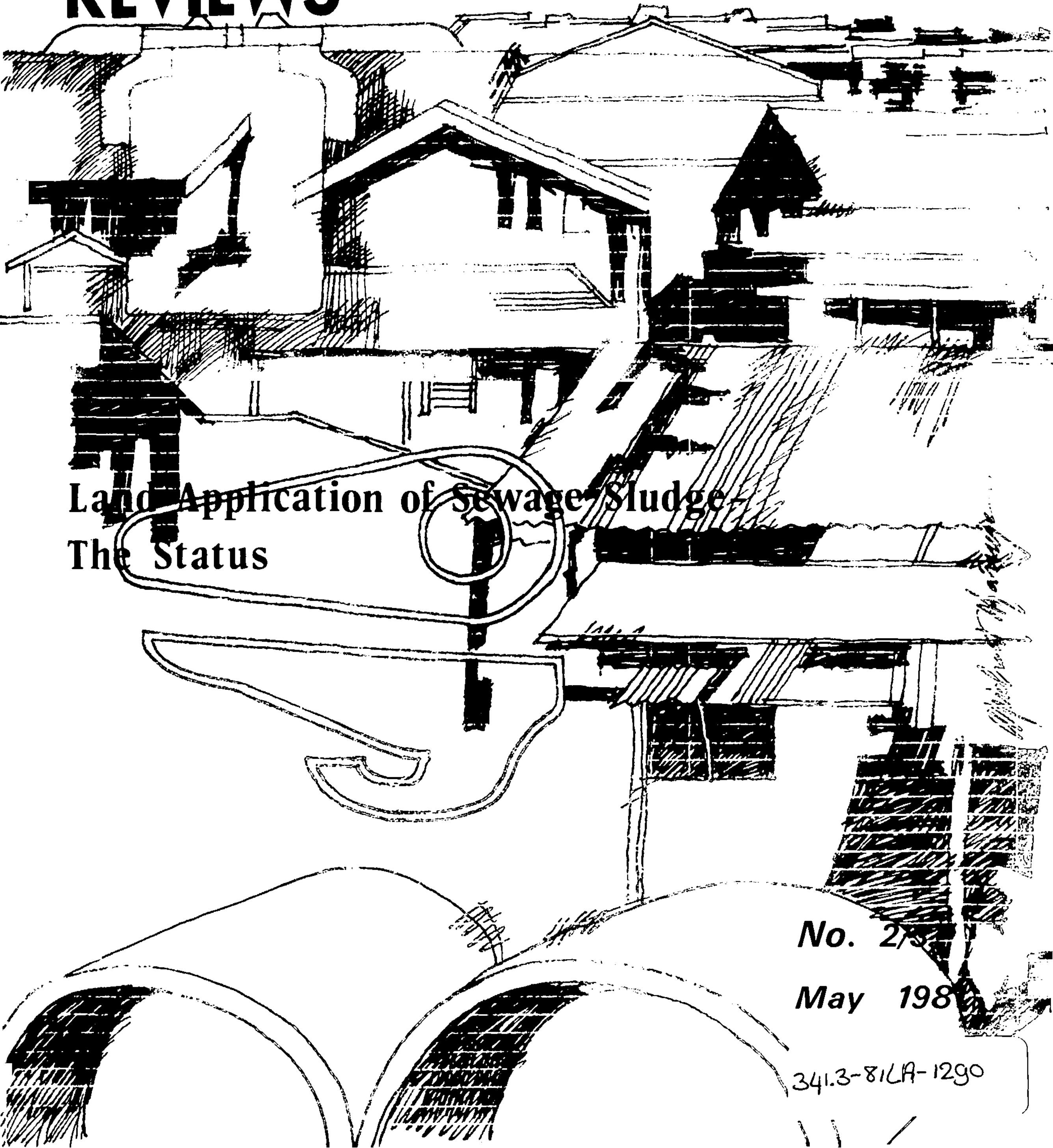

Land Application of Sewage Sludge - The Status

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LAND APPLICATION OF SEWAGE SLUDGE: THE STATUS

by

ENSIC Review Committee On Land Treatment

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ENVIRONMENTAL SANITATION INFORMATION CENTER

BANGKOK, THAILAND

MAY, 1981

PREFACE

The state-of-the-art on land treatment of municipal wastewater was published in the maiden issue of the Environmental Sanitation Reviews, August 1980. In compiling the same, the Committee attempted to present an overview of some of the important research findings in the field. Some comments received on the review stressed the need for a more field-oriented (practical) publication.

The present review on land application of municipal sludge is more detailed, in which the Committee has described the factors to be considered and some of the methodology outlined in the design and maintenance of such systems, in addition to outlining some salient research findings in the field. In compiling the review it was noted that most of the reports are from the developed countries and there is a dearth of literature on land treatment of sewage sludge from developing countries. However, it is hoped that a summary of the existing research in the field would stimulate possible activity in countries or regions not practising land treatment so far.

The application of nightsoil to land has been practised in many countries in the East for centuries, but it is not within the purview of this report. ENSIC anticipates having a separate report on nightsoil, its disposal, and the role of land treatment in such disposal, in due course.

This report is intended to supply information to a wide range of audience, including researchers, planners, educators -- anyone who is actively involved in the field. The Committee hopes to update the information from time to time as future developments take place in this rapidly advancing field.

ENSIC Review Committee on Land Treatment

K. Rajagopal
B. N. Lohani
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LAND APPLICATION OF SEWAGE SLUDGE

THE STATUS

****

by

ENSIC Review Committee on Land Treatment

K. Rajagopal
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1. INTRODUCTION.

1.1 The Sludge Problem

> Do you know what these piles of ordure are, those carts of mud carried off at night from the streets, the frightful barrels of the nightman, and the fetid streams of subterranean mud which the pavement conceals from you? All this is a flowering field, it is green grass, it is the mint and thyme and sage, it is game, it is cattle, it is the satisfied lowing of heavy kine, it is perfumed hay, it is gilded wheat, it is bread on your table, it is warm blood in your veins.
>
> Victor Hugo in 'Les Misérables'

The concept of land disposal of human waste is not new. Since the beginnings of recorded history, some countries in the East have realised the benefits of human excrement as a source of fertilizer. In Europe, the use of human wastes for farming dates back to the middle of the last century (1). With increased urbanization and population densities, sludge disposal has become a great challenge to be reckoned with.

In the United States, as in many other Western countries, sludge disposal on land for agricultural purpose has not been practised widely due to the availability of inexpensive and convenient inorganic fertilizer. The traditional method of sludge disposal in the U.S. used to be to haul it by truck to some hole in the ground and forget it (1). Recent enactment of the pollution control legislation in 1972, 1976 and 1977 and other environmentally related legislation has had an important impact on sludge management in the United States which can be summarised as (2): (i) Cleaner effluents, but greater quantities of sludge,

(ii) An end to ocean disposal of sludge by December 31, 1981, (iii) Emphasis on recycling and reuse of waste materials, (iv) Greater consideration of land application of sludge, and (v) Prevention of toxic levels of materials from entering the environment. Achieving these is going to be an arduous task considering that each year nearly 6 million dry tons (5.4 million dry tonnes) of sewage sludge are generated by wastewater-treatment plants in the United States (2).

The increasing population densities in large cities have resulted in the construction and expansion of numerous municipal wastewater treatment facilities and a consequent boost in sludge production. For example, it has been predicted that in New York State, the quantity of sludge generated annually may almost double during the years 1975-1985 from 356,000 dry tons to 689,000 dry tons (322,956 tonnes to 625,047 tonnes) (Fig. 1). Presently, over half of the sludge produced in the state (based on design flow) is barged to the ocean for disposal (Fig. 2). The remainder is disposed of by incineration (20%), landfilling (20%), and land application (5%). As a result of the federal mandate to end ocean disposal by the end of 1981, consideration being given to land application is increasing. Land-application programs for cities are complex because of the quantities of sludge involved, environmental monitoring requirement, large areas under management, and contamination by industry. For small communities whose sludge is not contaminated by industry, application of sludge to land can be a reasonable sludge management alternative. An important aspect of sludge management is for each community to develop a strategy employing one or more disposal methods that will provide a year-round, balanced program in which no segment of the environment is overloaded (2).

While the above information is applicable to the United States, similar trends can be expected as sewage treatment facilities are built or improved in other countries and as energy costs continue to increase. The sludge problem is a potential problem throughout the world and it would be prudent to consider environmentally-safe sludge treatment and disposal alternatives which are also cost effective.

This report has been undertaken to survey the existing sludge treatment alternatives and to summarize the present state of knowledge in the field of land application of sewage sludge to bring out its róle in present-day sludge treatment and disposal programs.

The scope of this report is limited to the following:

(a) A summary of research findings in the field of land application of sewage sludge. Although the literature quoted is mostly from the developed countries, notably the United States, it is hoped that the report will stimulate possible activity in other countries or regions not practicing land treatment of sewage sludge.

(b) The application of nightsoil to land which has been prevalent in developing countries like China for centuries has not been discussed here. This report is confined to the land treatment of sewage sludge from sewage treatment plants. ENSIC hopes to bring out a separate report on nightsoil, its disposal, and the role of land treatment in such disposal, in course of time.

(c) This review is confined to the beneficial utilization of sewage sludge for agriculture and for reclamation of disturbed lands, etc. Dedicated land disposal, the application of heavy sludge loadings to some finite land area which has limited public access and has been set aside or dedicated for all time to the disposal of wastewater sludge, has not been discussed here.

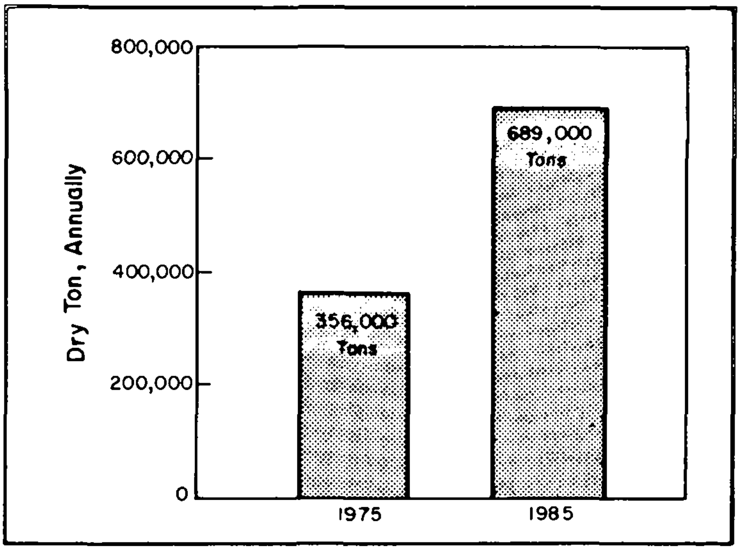

Figure 1. Sludge Generated in New York State (2).

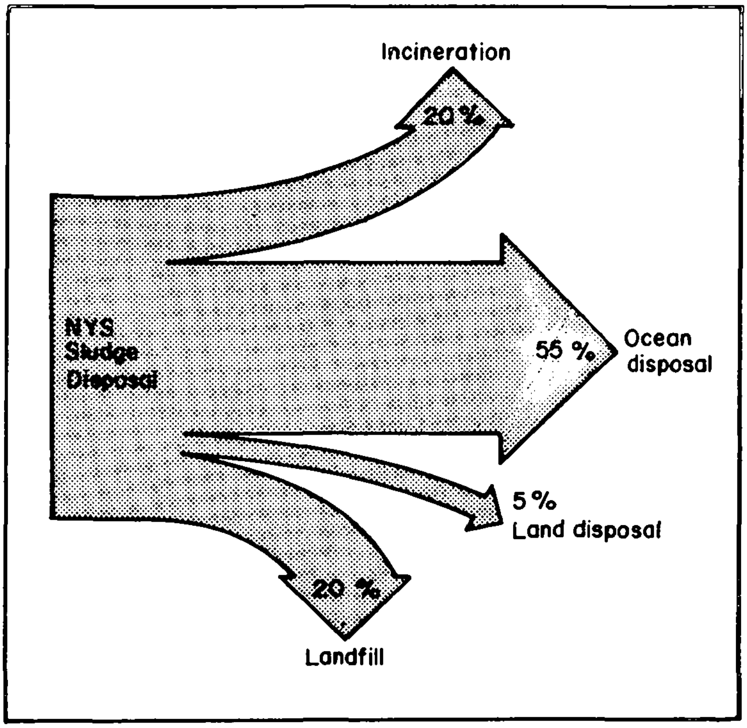

Figure 2. Sludge Disposal in New York State, 1976, Based on Design flow of Sewage-Treament Plant (2).

(d) The review is intended for a wide range of audience -- researchers, planners, educators, etc., may find it a useful source of information.

Before undertaking a sludge management program, it is necessary to have a thorough understanding of its composition, method of production, quantity of production, pretreatment needs, and the options available for disposal.

1.2 Sewage Sludge -- Defined

Sludge is the accumulated solids concentrated during the treatment of a community's wastewater.

Human activities -- restaurants, kitchens, industries, bathrooms, and business -- produce wastewater, which contains various amounts of dissolved and suspended organic and inorganic solids. The purpose of wastewater treatment facilities is to remove these pollutants, whatever their form, before discharging the treated water into the environment. Substances entering a wastewater-treatment plant are discharged either with the treated water or in the sludge. Exceptions are volatile organic compounds and gases contained in the wastewater or produced during its treatment, which are discharged to the atmosphere. As a result, the purer the effluent from the treatment plant, the greater the quantity of sludge generated (3).

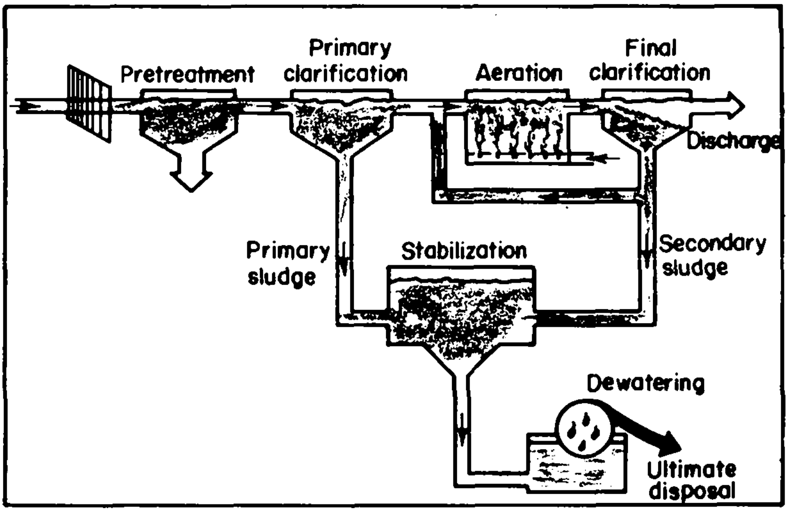

Figure 3. Typical Wastewater-Treatment Plant Processes (3).

1.3 Method of Production and Sludge Types

A wastewater treatment plant removes pollutants in two major ways: by settling out suspended solids (primary treatment) and by converting dissolved solids into suspended solids (secondary treatment) that subsequently are removed. A diagram of a typical wastewater treatment system is shown in Fig. 3 (3). During primary treatment, wastewater flows to a clarifier where suspended solids settle out by gravity and are referred to as primary sludge. Secondary treatment is generally a biological treatment process, in which microorganisms metabolize dissolved solids such as carbohydrates, fats, and proteins and produce new microorganisms, which become suspended solids. The processed wastewater flows to a secondary clarifier where the suspended microorganisms are removed by settling. These solids are referred to as secondary sludge.

1.4 Quantity of Sludge Production

In an average community in the U.S., a family of four is estimated to generate about a pound (0.45 kg) of sludge (dry weight) per day. For a community of 1000 residents with secondary treatment of wastewater, this results in about 250 pounds (113.64 kg) of dry sludge solids per day. During a period of a year, over 90,000 pounds (40,909 kg) of sludge (dry weight) are generated.

Although sludge is normally handled as a liquid or a slurry, its quantity is usually expressed in terms of dry weight. Dry weight is used to estimate and compare sludge quantities because, depending on how it is produced and processed sludge can contain varying proportions of water. Most wastewater treatment plant sludges contain about 95 to 98 percent water, or 2 to 5 percent solids. The relative proportion of water to solid material in sludge is illustrated in Fig. 4 (3).

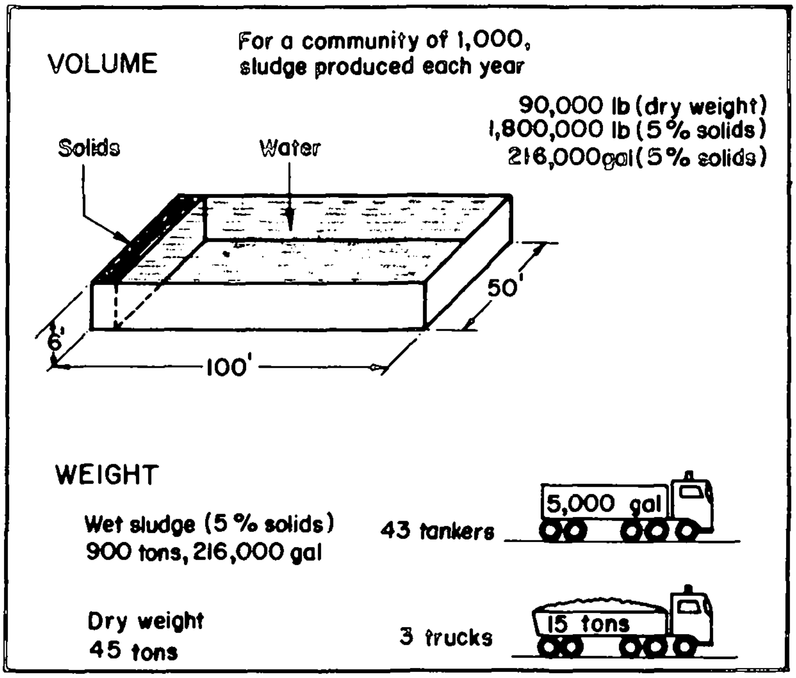

Figure 4. Dewatering Reduces Volume and Weight of Sludge (3).

In the previous example of 1000 residents, at 4 percent solids, the 90,000 pounds (45 tons) of sludge, dry weight, turns out to be over 2 million pounds (907 tonnes), wet weight -- nearly 270,000 gallons. That is enough sludge to fill a pool 50 feet (15.2 m) wide, 100 feet (30.3 m) long and 7 feet (2.1 m) deep. Managing this quantity of sludge is not a major problem over a period of a year. However, in the case of large cities, most of the sludge is generated by large wastewater treatment plants. For example, the New York City Metropolitan area is projected to generate about 150,000 tons (136,077 tonnes)of dry solids each year by 1985. At 4 percent solids, this amount is equivalent to about 4.5 million tons (4.08 million tonnes), wet weight, per year. Spread 1 foot thick on land, this quantity would cover 3,300 acres (1336 ha). However, if the sludge is applied to agricultural land, a 2-inch annual application is typical. The required land area now becomes nearly 20,000 acres (8097 ha). Management of this quantity of sludge can be a major problem (3). What applies to New York City may apply to many other metropolitan cities of the world also.

For example, in the case of India, it has been estimated that if the entire domestic wastes of all towns of India are utilized, it can irrigate more than 200,000 hectares of land (221). In Bangkok the sewage sludge production from cesspools and septic tanks was assessed to be about 150,000 cubic meter in 1977, without considering the sludge from central treatment plants (222). The volume of sewage sludge produced in Tokyo after secondary treatment by eight wastewater treatment plants presently operating in the inner city is about 3400 tonnes (25% of solid content). The sludge produced from proposed advanced wastewater treatment will add tremendously to this volume of sludge. Out of this 3400 tonnes of sludge cake produced, about a half is incinerated and the remaining amount is used for land reclamation (223). There are reports from Germany (157) that 18 million tonnes of domestic refuse could be applied to farmland annually. The total production of sewage sludge in England and Wales in 1970 was reported as 1.1 m tons (1.0 m tonnes) (39). It may be expected to be much higher now.

Thus it can be seen that the potential sludge problem is ubiquitous and is envisaged to escalate with increased urbanization, increasing population densities, and the construction and improvement of sewage treatment facilities.

1.5 Sludge Constituents

For a community to develop a sound sludge management plan, it is necessary to have a better understanding of what sludge contains. Although no two sludges are identical, some generalizations can be made about their physical, chemical and microbiological characteristics.

Sludge is the solids concentrated by the treatment of municipal wastewater and contains impurities removed from the wastewater. It is a non-sterile by-product of a community and contains both organic and inorganic materials. Sludge can have an odor from tarlike to putrid. Its color can range from rich black to an earthy brown. The general physical characteristics of various sludge types are shown in Table 1 (4). Primarily, sludge is water, as much as 99 percent in some cases. What is important is what it contains besides water. Because sludge is a by-product of the food we eat, it contains many of the same elements as our food: nitrogen, phosphorus, potassium, iron, calcium, sodium, and other elements. Typical chemical composition of raw and digested sludge is noted in Table 2 (4). Some chemical characteristics as reported in English literature (39) are given in Table 3 and the characteristics of sewage sludges in Asia are given in Table 4. Table 5 depicts the characteristics of sewage sludges in some German cities.

Because sludge is a product of the human population of a community, it contains many microorganisms. Some microorganisms break down organic materials; others synthesize new compounds. Some cause diseases; others inhibit the growth of pathogens. Some organisms are rare; some are abundant; some we know little about. Unless sterilized, sludge always contains microorganisms, some of which may be harmful or pathogenic. Because sludge is a product of a community, it

Table 1. General Physical Characteristics of Various Types of Sludge (4).

Sludge	Color	Other Physical Properties	Odor	Digestibility (Amenability to Further Biological Stabilization)
Primary sedimentation	Gray	Slimy	Extremely offensive	Readily digested
Chemical precipitation (primary)	Black, red surface if high in iron	Slimy, gelatinous, gives off considerable gas	Offensive	Slower rate than primary sedimentation
Activated sludge	Brown, dark if nearly septic	Flocculent	Inoffensive, earthy when fresh; putrifies rapidly	Readily digested
Trickling filter humus	Brownish	Flocculent	Relatively inoffensive, decomposes slowly	Readily digested
Digested sludge	Dark brown to black	Contains very large quantity of gas	Inoffensive if thoroughly digested; like tar or loamy soil.	Well stabilized
Septic tank sludge	Black		Offensive (H_2S) unless very long storage time	Mostly stabilized

Table 2. Typical Chemical Composition of Raw and Digested Sludge (4).

Item	Raw Primary Sludge		Digested Sludge	
	Range	Typical	Range	Typical
Total dry solids (TS), %	2.0-7.0	4.0	6.0-12.0	10.0
Volatile solids (% of TS)	60-80	65	30-60	40.0
Grease and fats (ether soluble, % of TS)	6.0-30.0	–	5.0-20.0	–
Protein (% of TS)	20-30	25	15-20	18
Nitrogen (N, % of TS)	1.5-4.0	2.5	1.6-6.0	3.0
Phosphorus (P_2O_5, % of TS)	0.8-2.8	1.6	1.5-4.0	2.5
Potash (K_2O, % of TS)	0-1.0	0.4	0.0-3.0	1.0
Cellulose (% of TS)	8.0-15.0	10.0	8.0-15.0	10.0
Silica (SiO_2, % of TS)	15.0-20.0	–	10.0-20.0	–
pH	5.0-8.0	6.0	6.5-7.5	7.0
Alkalinity (mg/l as $CaCO_3$)	500-1,500	600	2,500-3,500	3,000

Table 3. Analysis of Some Sewage Sludges (39).

Type	% Dry Solids	Valatile Matter	Nitrogen as N	% on dry solids Phosphorus as P	Grease	Detergent as Manoxol O.T.
Thickened raw sludge	5.7	73	4		20	1.0
Thickened surplus activated sludge (fully) nutrifying)	2.8	78	8-9	2.5-3		0.5
Digested sludge (Mixture of above, heat digested)	2.8	63	7	2.5	4	1.3-1.4
Humus sludge	3.0	65				0.2

Table 4. Characteristics of Some Wastewater Sludges from Asia (224).

Type of Sludge	Source	Date Collected	Solids Content (%)	Volatile Solids (%)	pH	Volatile Acids (mg/l)
Raw primary sludge	Ulu Pandan Sewage Treatment Plant, Singapore	March 1965 – Mean	4.5	80	5.8	860
	Odai Sewage Treatment Plant, Tokyo, Japan	July 1964 – Mean	5.1	43	6.2	–
Night soil	Unspecified, Japan	1962	1.9-4.2	45-67	7.8	–
	Taipei, Taiwan	1956-7 Summer Mean	2.73	63	9.4	–
		Winter Mean	2.87	60	8.9	–
Night soil sludge	Unspecified, Japan	1962	3.7	40	8.6	–
	Bangkok, Thailand	1965-67 Minimum	1.25	60	6.9	360
		Mean	3.65	67	7.7	750
		111 Maximum	6.40	71	8.5	1,700
Septic tank sludge	Bangkok, Thailand	1965-67 Minimum	1.1	44	7.0	120
		Mean	3.1	71	7.8	320
		Maximum	5.6	90	8.5	950
Digested sluuge	Odai Sewage Treatment Plant, Tokyo, Japan	July 1964 – Mean	5.6	32	7.3	500
	Ulu Pandan Sewage Treatment Plant, Singapore	March 1965 – Mean	9.0	58.5	7.1	83

Table 5. Composition of Sewage Sludge Produced at 7 German Cities (157).

Parameter			*number of samples (n)*	*average (x)*	*Contents min.*	*max.*
Dry matter		%	540	39.0	2.6	93.3
Loss by ignition		%	538	48.4	3.0	82.0
Total – C		%	163	22.8	1.3	38.0
Major Nutrients						
Nitrogen	(N)	%	596	2.36	0.4	12.3
Phosphorus	(P)	%	610	1.47	0.2	4.9
Potassium	(K)	%	608	0.16	0.017	1.15
Calcium	(Ca)	%	610	6.56	0.5	39.9
Magnesium	(Mg)	%	608	0.12	0.0	1.14
Sodium	(Na)	%	370	0.39	0.03	0.96
Trace Elements						
Boron	(B)	ppm	505	18.4	0.9	358
Copper	(Cu)	ppm	610	387	20	2,600
Manganese	(Mn)	ppm	529	335	57	1,245
Zinc	(Zn)	ppm	610	2,141	70	15,750
Toxic Elements						
Cadmium	(Cd)	ppm	538	20.7	1	150
Lead	Pb)	ppm	609	290	19	1,500
Nickel	(Ni)	ppm	94	131	22	200
Mercury	(Hg)	ppm	36	4.8	0.1	55

contains constituents introduced to the wastewater from industries, commercial establishment, street runoff, homes, and even the water we drink. A community may contain industries such as food processors, electroplaters, and refineries. Each industry contributes to the wastewater stream and, ultimately to the character of the sludge generated at the wastewater treatment plant. Even the most careful industry will discharge some inorganics with its wastewater. Some of these are relatively harmless, such as sodium, potassium, calcium, and magnesium. Other, such as the metals cadmium, lead, nickel, and copper, can be of concern to various forms of life, especially when present above certain threshold concentrations. Table 6 gives typical values for metals in various sludges (5).

Thousands of toxic organic chemicals are used and produced by industries. Many are discharged to the municipal treatment plant and may ultimately end up in the sludge. The presence of toxic and hazardous chemicals in wastewater has caused problems with both wastewater treatment and sludge disposal. As a result there has been increased emphasis on reducing the amount of all toxic contaminants discharged to municipal wastewater treatment plants. Industries are not the sole contributor of contaminants to wastewater. Commercial establishments such as retail stores, restaurants, laundromats, garages, hospitals, schools, laboratories, and photo processors contribute to the load of

Table 6. Typical Values for Metals in Sludges (5).

Metal	Value, ppm Range	Mean	Median
Silver	nd*-960	225	90
Arsenic	10-50	9	8
Boron	200-1,430	430	350
Barium	nd-3,000	1,460	1,300
Beryllium	nd	nd	nd
Cadmium	nd-1,100	87	20
Cobalt	nd-800	350	100
Chromium	22-30,000	1,800	600
Copper	45-16,030	1,250	700
Mercury	0.1-89	7	4
Manganese	100-8,800	1,190	400
Nickel	nd-2,800	410	100
Lead	80-26,000	1,940	600
Strontium	nd-2,230	440	150
Selenium	10-180	26	20
Vanadium	nd-2,100	510	400
Zinc	51-28,360	3,483	1,800

*nd = not detected.

wastewater contaminants. Stormwater runoff from areas served by combined sewers contains zinc and cadmium from tire wear, lead from gasoline, metals from gutters, and corrosion from other metal objects. The household itself is a source of contaminants. Home plumbing (copper and galvanized water pipes), household commodities (detergents, bath soaps), and solids from garbage grinders contribute to wastewater. Practically all municipal water supplies, whether from groundwater or surface waters, contain at least trace concentrations of many metals. These materials are concentrated by wastewater treatment processes and can be a major source of some metals in sludge (3).

Whatever disposal option is chosen by a community, sludge is generally processed in some way to produce a sludge more amenable to a desired disposal option or easier to handle, or both. The next section will briefly review the different processing techniques available for sludge.

1.6 Sludge Processing

Sludge can be processed physically, chemically, or biologically. Processing techniques fall into two general categories: Stabilization and Dewatering.

(a) Stabilization.

All sludges are called raw sludges until they are stabilized in some way to avoid public health and environmental problems. Because of odor problems and the presence of active pathogenic bacteria, disposal of raw unstabilized sludge is rarely done. Stabilized sludge results from processing methods that reduce the odor potential and the number of pathogenic organisms. Several methods follow: anaerobic and aerobic digestion, composting, lime stabilization and chlorine stabilization.

(i) Anaerobic Digestion.

This is a natural process in which microorganisms that thrive in the absence of oxygen biologically break down organic solids. The process is confined to closed containers or tanks (digesters), many of which have heating and mixing systems. Sludge is retained in the digesters for 10-30 days at temperatures of 80 to 110 degrees Fahrenheit (26.7 to 43.3 degrees Centigrade). As a result of the biological activity, a number of beneficial changes occur in the sludge:

* Methane gas is produced; thus the digesters can be heated by their own fuel production.

* The weight of the dry matter in sludge is reduced by about 40-60%.

* Survival of pathogenic organisms is significantly reduced.

* Potential for odors is greatly diminished.

(ii) Aerobic Digestion.

In aerobic digestion, air is used to stabilize sludge in a manner similar to that of aeration processes used in treatment of wastewater. Sludge is aerated in an open tank for 10 to 15 days. Changes in the sludge are similar to those for anaerobic digestion except that methane is not produced.

(iii) Composting.

One important advantage of composting is that a product, virtually pathogen-free, dry and free flowing, and bearing little physical resemblance to the original material, is produced. In this context it may be relevant to mention the aerated-pile composting method developed by the United States Department of Agriculture at Beltsville, Maryland, which is particularly suitable for land application of sludge (6,207). The method is illustrated in Figs. 5 and 6 and consists of the following steps:

* Preparation: For good composting a moisture content of 40% to 60% is required. Wet sludges are about 95% moisture, and dewatered sludges generally contain about 75% moisture. To decrease the moisture content, a dry bulking material, such as wood chips, sawdust, or shredded tires, is added.

* Decompostion: The compost mix is piled in long rows called windrows. Air, supplied by periodic turning of the pile or mechanical aeration, helps microorganisms oxidize organic material and generate sufficient heat to raise the temperature of the pile to between 140 and 160 degrees Fahrenheit (60 and 71 degrees Centigrade). After 2 to 3 weeks of processing, the composted sludge is stabilized. Odor potential of the compost is minimal. An important benefit is that composting temperatures and processing time combine to eliminate virtually all active pathogenic organisms and provide a stable, low moisture product.

* Curing: Curing follows the decomposition step and is considered an extension of the composting process. Pile temperatures decrease to ambient during the 30 to 60 day curing time, and the process is brought to completion.

* Finishing: Following curing, the compost can be screened or graded to provide a product free of large of non-digestible debris. The composted sludge has little odor, practically no pathogenic organisms, and is dry enough to be stored easily.

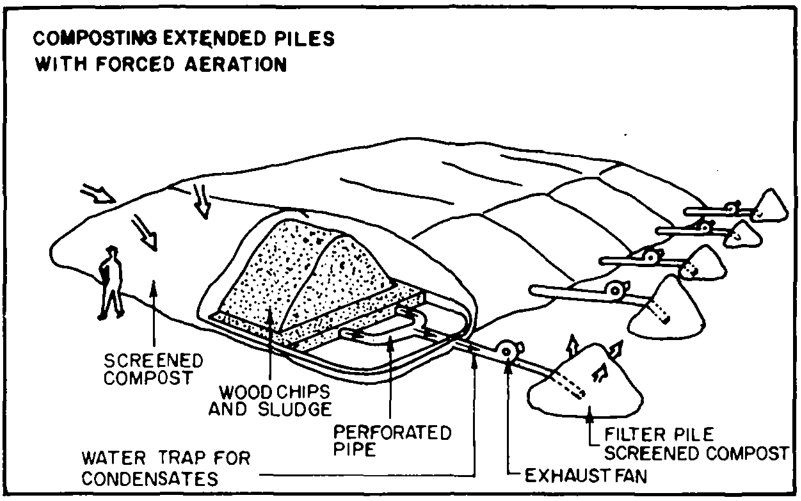

Figure 5. Sludge Composting for Land Application (6).

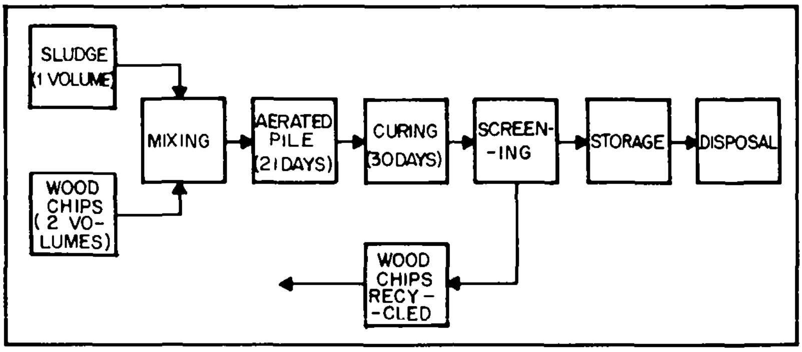

Figure 6. Aerated - Pile Composting Processes (6).

Bench scale vermicomposting studies conducted by HARTENSTEIN, et al. (228) using earthworms like Eisenia foetida indicate that a potential exists for use of certain earthworm species to convert the entire output of municipal sludge into marketable commodities.

(iv) Lime Stabilization.

Lime stabilization is a chemical process involving the addition of a bulk chemical (lime) in sufficient quantity to maintain a very alkaline environment (pH 11-12) for several hours. Although the process kills bacteria as effectively as digestion, the quantity of sludge solids is increased by 10% to 50% because of the addition of lime.

(v) Chlorine Stabilization.

Another chemical stabilization process is chlorine stabilization. Very high doses of chlorine are added, virtually sterilizing the sludge. The residue dewaters well on sand drying beds and has long term stability. However, its high acidity (about pH 2), coupled with the formation of high concentrations of chloramines and other chlorinated hydrocarbons, has caused concern regarding disposal of the chlorinated solids in the environment.

(b) Dewatering.

Raw and stabilized sludges may contain 90% to 99% water. To improve handling, processing, transportation, and disposal, removal of as much water as possible from the liquid sludge mixture is desirable. Dewatering also substantially reduces management costs. Sludge dewatering can be accomplished either mechanically or by gravity. Several methods follow:

(i) Sand Drying Beds.

Sand drying beds are commonly used at treatment plants to dewater stabilized sludges. The sludge is spread on the sand, and dewatering is accomplished by drainage and evaporation. Most of the water is lost by drainage within several days of application. Subsequently, evaporation is the principle effect. After several weeks, the solids content may increase to between 15% and 20% and the dewatered sludge can be removed easily for ultimate disposal.

(ii) Vacuum Filters.

Vacuum filters can be used to dewater both raw and digested sludges. It is a continuous mechanical process and requires far less space than gravity-drained sand beds. In vaccum filtration, a large drum is suspended above and into a tank of sludge. As the drum rotates slowly, the submerged part of its surface is subject to an internal vacuum, causing the sludge solids to adhere to the surface. The liquid filtrate moves through the filter surface and is returned to the treatment plant. Typical solids content of the dewatered sludge cake is 15% to 25%. In case of the filter press and belt filter press, although the equipment used differ greatly, in both cases the sludge is pressed against some type of support. Solids remain on the surface, and the filtrate passes through and is further treated. The solids content of the cake is similar to that resulting from vaccum filtration.

(iii) Centrifuges.

In this process liquid sludge is fed into a spinning container. The solids separate into a dense cake on the inside surface. The effluent from the system is returned to the treatment plant. The solids content of the dewatered sludge is typically 15% to 25%.

Properly planned sludge processing can reduce the cost of disposal to the community and help to avoid environmental and public health problems during disposal (6).

Once the sludge is processed and ready, it has to be disposed of. Ultimately, all the materials in sludge must be returned to the environment, and the only options are air, water or land. Whichever option is chosen, the impact on the environment must be weighed carefully.

1.7 Sludge Disposal Options

Each sludge, like each community, is unique. No one disposal alternative will be the best for every community or every type of sludge. Each alternative has its benefits, problems, and costs. As a community evaluates sludge disposal alternatives, it must weigh energy efficiency (including transportation distance, energy or fuel used for processing and transportation), environmental protection (including characteristics of the sludge, availability of land, soil characteristics, present and future crops, air pollution, groundwater and surface water protection) and economics (including labor, capital costs, maintenance, energy costs and land price). At the facility planning stage, a checklist, like the one established by the U.S. Environmental Protection Agency (205), may be used to make sure that all feasible sludge management alternatives were properly considered. When a particular concept has already been selected, again, checklists may be used to evaluate the design, and operation and maintenance of the system to ensure a proper running of the project (205).

Sludge disposal is the process of transferring the sludge to the environment so that further handling or processing is not necessary. The various disposal options are (i) landfill, (ii) lagooning, (iii) ocean disposal, (iv) incineration, and (v) land application. Each has some benefits and problems associated with it. The first four options will be discussed briefly. Land application will be discussed in detail.

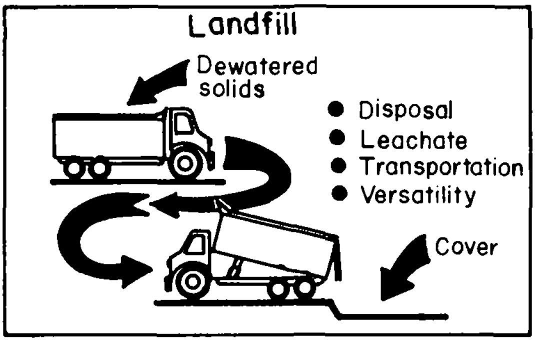

Figure 7. Landfilling of Sludge (7).

(i) Landfill.

Landfilling of sludge (Fig. 7), along with solid waste is commonly used. Landfills have the advantage of being owned by the community, which has complete control over site management. They are usually separated from residential areas to minimize complaints and generally provide year-round access. Landfilling of sludge can be the best solution for some communities. For example, the sludge generated by the community may contain levels of heavy metals and other chemicals toxic to wildlife, domestic animals, and humans. In other cases, agricultural land may not be available, or economic considerations may preclude other disposal options.

Landfilling is not without its drawbacks. In a landfill essential plant nutrients are buried with the sludge. In addition, landfills are not isolated completely from groundwater. There is a real possibility that leachate from a landfill site may contaminate groundwater supplies, although the problem may not be apparent for years (7). Disposal of natural or chemically fixed sludges by landfilling requires suitable sites to prevent groundwater pollution, and these are becoming increasingly difficult to obtain (8). Nonetheless, proper landfill design, location, and management can minimize the groundwater-contamination concern (7).

(ii) Lagooning.

Lagooning of sludge has been a popular "disposal" method because it is simple and economical, provided the lagoon site is in a remote area. With this method the treatment-plant sludge is pumped to a pond or lagoon for storage, sometimes for many years, until ultimate disposal.

In a lagoon, solids settle, accumulate, and decompose. Excess liquid, if any, is returned to the plant for treatment. If the lagoon is used only for digested sludge, nuisance problems such as odors are minimal. However, even after draining and drying, the sludge must be removed and disposed of, such as in a landfill or on available land. In this sense, lagooning falls in between a dewatering process and disposal (7).

(iii) Ocean Disposal.

Disposal of sludge at sea has been used by several large coastal cities such as Boston, New York City, Los Angeles, etc., for many years. Ocean disposal for such cities is convenient and economical. Sludge can be barged many miles off-shore and discharged (as in New York City), or pumped several miles from shore into deep water, through an underwater outfall (as in Los Angeles).

Dispersion by swift currents, containment at great depths, or disposal many miles from shore tend to prevent environmental or esthetic problems. However, metals and other sludge constituents have been recognised as potentially harmful to aquatic life. In the U.S., a ban on ocean disposal of sludge is set for December 31, 1981 in view of the above mentioned hazard (7).

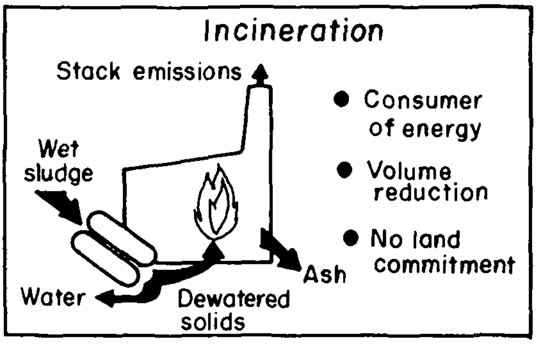

Figure 8. Incineration of Dewatered Sludge (7).

(iv) Incineration.

Incineration (Fig. 8) is not a complete disposal option. This method reduces both the volume and weight of a sludge by perhaps 90%, but produces an ash byproduct. During incineration, temperatures of 1350 degrees Fahrenheit (732 degrees Centigrade) or more dry the sludge to the point at which organic matter can be burned. Thus, energy is both consumed and generated during the process. Sludge must contain at least 25% to 30% solids for combustion to proceed without the addition of supplemental fuel. To increase the solids content of sludge from about 4% as it comes from the treatment plant to 30%, ready for combustion, dewatering is required.

There are several benefits of sludge incineration before disposal. Some sludges may contain high enough concentrations of undesirable contaminants to preclude their disposal on the land. Land for disposal of sludge may be expensive or unavailable near some treatment plants, particularly those in metropolitan or suburban areas. If the sludge must be transported long distances for disposal, transportation costs of the by-product ash to a final disposal site will be much less than for the wet sludges. Residual ash from the incineration process is usually landfilled. With a well-managed operation and regularly maintained equipment, sludge incineration can generate more energy than it consumes, and energy recovery has been suggested. Though energy recovery is theoretically possible, few successful heat recovery systems are in operation.

The drawbacks of incineration are its high capital expense, consumption of large quantities of fuel where heat recovery is not practised, and pollution of the atmosphere (8). Some of the heavy metals in sludge such as lead, mercury, and cadmium may vaporize at incineration temperatures and are released to the atmosphere (7). Moreover sludges can be 50 percent ash which still requires disposal in landfills. Hence, it is not a complete disposal option.

(v) Land Application.

In the past 10 years, application of sludge to available land has received a great deal of attention by agriculturists, wastewater treatment operators, and environmental and public health officials. Although land application of sludges has been practiced for decades in the United States and other countries, there is concern about the harmful materials in the sludges. However, the nutrients and organic matter in sludges are of value in crop production, especially as fertilizer costs increase and farmers seek to maintain the fertility of the soil.

Although sewage sludges contain plant nutrients and humus important to a fertile soil, they may also contain pathogenic organisms and certain metals such as cadmium, copper, and nickel, in high enough concentrations to be harmful to plants, animals, and humans. These components may result in either short-term or long-term impacts. As a result, application of sludge to land requires a thorough understanding of sludge-soil-crop interactions, both beneficial and potentially harmfull, which aid in establishing an efficient and sound state-of-the-art for land application of wastes (7).

The recent upsurge of interest in land application of sludge has triggered of extensive research in the field, and detailed reports and manuals have been published which are very useful in the design and maintenance of such systems (45,207,219,220). This review merely provides some of the latest thinking and information in the field which, it is hoped, will serve the needs of those who are actively involved in the field.

Readers are again reminded that the scope of this review is limited to the beneficial utilization of sewage sludge for agriculture and for reclamation of disturbed lands, such as stripmined lands, etc. Dedicated land disposal (the application of heavy sludge loadings to some finite land area which has limited public access and has been set aside or dedicated for all time to the disposal of wastewater sludge) has not been covered. Information on this is given elsewhere (207).

2. BENEFITS FROM LAND APPLICATION OF SLUDGE.

The unfavourable attitude towards sludge application on land is due to the fact that for a long time sanitary engineers in general have looked at the sludge problem "as a question of destruction of noxious matter rather than conservation of values". Moreover, insufficient knowledge of its value, unsuitable methods for its use and preparation, as well as exaggerated propaganda and little interest on the part of the sellers have retarded its use (11).

2.1 Fertilizer Value of Sludge

Sludge has an appreciable nutrient value and these are wasted for the most part when disposal options like ocean disposal, landfilling or incineration are resorted to. For example, in the U.S.A., about $93 million worth of nitrogen, phosphorus and potassium as fertilizer were present in sludge in 1978. Energy is required to produce synthetic fertilizer in place of the wasted sludge nutrients. 420 gallons of crude oil per ton would be required to manufacture the nitrogen destroyed by incineration or 23 million gallons of oil to manufacture the estimated 55,000 tons (49,895 tonnes) of nitrogen wasted in 1978. Moreover, about 120 million gallons of number 2 fuel oil would be required to burn the 2.4 million dry tons (2.18 million dry tonnes) of sludge incinerated in 1978, thereby increasing the total fuel consumption to about 143 million gallons, i.e. enough to supply the heating needs for say approximately 139,000 homes (1700 square feet in size) in Minneapolis, MN or 622,000 similar homes in Atlanta, GA for one year (12). This interpretation of the magnitude of the fertilizer value lost by resorting to disposal options other than land application, clearly emphasizes the need to consider seriously the feasibility of using sewage sludge as a fertilizer.

Table 7. Nutrient Content of A Typical Sewage Sludge (9).

	N	*P*	*K*
Dry weight basis	2-4%	1-3%	0.1-0.5%
25% Solids	0.5-1	0.2-0.8	0.2-0.1
5% Solids	0.1-0.2	0.5-0.15	0.005-0.025

Municipal sludge usually contains most plant nutrients but its fertilizer value varies according to the source of the waste, characteristics of the sludge, wastewater treatment and its efficiency, and storage and handling employed prior to land application (4,10,13-15). Though sludge contains nitrogen, phosphorus, potassium, and trace minerals, the content of these fertilizing elements in sludge is low, or in other words, it is a low analysis fertilizer. On a dry weight basis, the nutrient composition of a typical sludge, given in Table 7, is approximately equivalent to a 3-2-0 fertilizer (9). The nutrient value of sewage sludge as reported from Germany may be inferred from Table 5.

One property of sludge that distinguishes it from commercial chemical fertilizers is that not all its nutrients are immediately available for plant uptake. For example, as the content of inorganic forms of nitrogen (ammonium and nitrate) decreases and as the organic nitrogen becomes more stable as a result of digestion processes in the sewage treatment plant, the availability to plants of the nitrogen in sludges decreases. If one-half of the total nitrogen is present as mineral nitrogen and if there are no losses during and following application, the proportion of the nitrogen that is available for uptake by plants in the first year after application could be as high as 70%. On the other hand, if all the mineral nitrogen has been lost and if the sludge is highly stabilized, the proportion of the nitrogen that becomes available for uptake by plants may be as low as 5 to 10% during the first year. Phosphorus and potassium in sludges are, however, considered to be as available as the usual sources of these elements in chemical fertilizers (10).

Depending on handling, sludges may contain different amounts of ammonia nitrogen (9). Because ammonia is immediately available for crop uptake, the ammonia content of a sludge will affect a sludge application rate based on nitrogen. As mentioned before, in general, sludge dewatering and stabilization processes that increase the pH of sludge (such as lime stabilization) or dry it by exposure to air (such as drying on sand beds) will decrease the nitrogen content of sludge because of loss of ammonia. Application methods that expose the sludge to the air, such as spray irrigation, or allow it to dry on the soil surface also enhance ammonia loss by volatilization. Injecting or plowing sludge into the soil tends to conserve nitrogen.

When sludge is applied to soil, it begins to decompose through microbial action. Organic nitrogen is broken down slowly, releasing nitrogen in the ammonium form. About 15 to 30 percent of the organic nitrogen is mineralized in this way within the first year after application of the sludge. Smaller amounts become available in succeeding years. In well-drained soils, further microbial action by aerobic bacteria (nitrifiers) converts ammonia nitrogen into nitrate nitrogen (nitrification). Inorganic forms of nitrogen (ammonia or nitrate) can be used immediately for crop growth. Taken up by plants, these inorganic forms are converted into plant proteins. However when nitrogen is in the nitrate form, it is easily leached downward by water percolation through the soil. Under these conditions, nitrate contamination of groundwater may occur if nitrogen application rates are greatly in excess of amounts that can be used by plants. In soils that are wet for extended periods, anaerobic conditions occur within the soil, and microorganisms convert nitrate nitrogen into nitrogen gas (denitrification). Typical nitrogen transformation and movement of the different forms of nitrogen are illustrated in Fig. 9. Thus it can be inferred that the methods of sludge processing, the mode of application, and soil conditions influence the type and rate of nitrogen transformation and consequently the amounts of nitrogen actually available for plant growth (9).

The phosphorus content of sludge may equal that of nitrogen. However the behaviour of phosphorus in the soil is greatly different from that of nitrogen. There is little potential for phosphorus contamination of groundwater because of the capacity of the soil to adsorb phosphorus. Good soil tillage practices will prevent erosion and runoff. Phosphorus in sludge can be used for plant growth, although about 10 to 30 percent is organically bound and not immediately available (9).

One critical issue that has to be faced sometimes is the large amount of liquid or dewatered sludge that must be applied to supply a certain quantity of nutrients. If we assume that dry sludge solids contain 5 percent N and 3 percent P, an application rate of 5 tons (10,000 pounds) of dry sludge solids per acre (11.2 tonnes/ha) would supply 500 pounds (227 kg) total N and 300 pounds (136

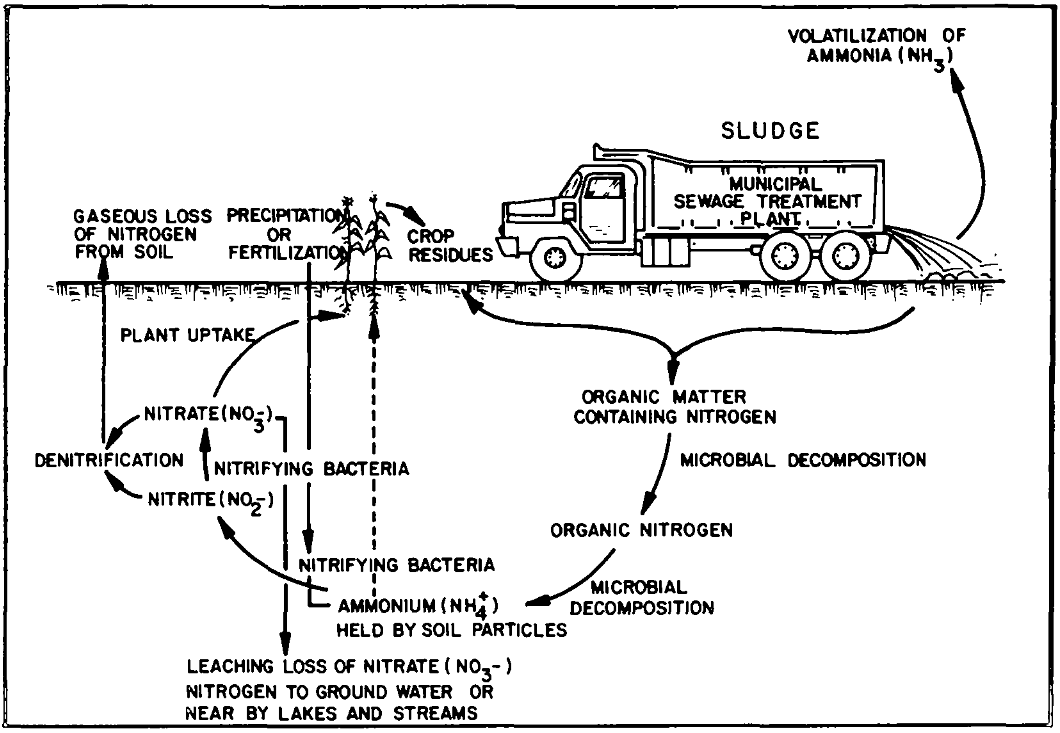

Figure 9. Recycling Nitrogen In Natural Processes (9).

kg) total P (690 pounds or 314 kg P205) per acre. To apply this 5 tons of dry sludge solids per acre, 167 tons (152 tonnes) of liquid sludge containing 3 percent solids would be needed, or 100 wet tons (91 wet tonnes) for a sludge with 5 percent solids. These would be equivalent to a layer of wet sludge about 1.5 inches and 0.9 inch (3.8 cm and 2.3 cm) deep, respectively. The farmer might find the cost of transporting and applying volumes such as these uneconomical if he bears it alone, since he can handle and apply much smaller quantities of commercial fertilizers for the nutrients his crops need. This problem can be overcome, if the municipality assumes part or all of this expense. Addition of other macro- and micronutrients may also be beneficial for some soils (8).

Data on the growth of crops due to sludge addition have been widely published. Corn and potato yield response to sewage sludge application is shown in Table 8, which point to the immense benefits that can be accrued from land application of sludge (1).

2.2 Sludge as a Soil Conditioner

Sludge is beneficial to the soil as a conditioner or builder. Contributing to the value of sludge as a soil conditioner is its content of organic matter, or humus (9). About one-third of digested sludge solids constitute humus or humus-forming matter (15). The organic matter helps to hold

Table 8. Corn and Potato Yield Response to Application of Sewage Sludge on a Hubbard Sandy Loam (Cited in 1).

Corn		Potatoes	
Sludge Application Rate (tonne/ha)	Grain Yield (kg/ha)	Sludge Application Rate (tonne/ha)	Potato Yield (kg/ha)
0	727	0	18,500
81	10,100	112	44,200
159	10,600	225	53,100
320	11,600	450	66,600

Note: Municipal sludge from sand drying bed; 24% solids, 1.3% N, 1.8% P.

plant nutrients in the soil and releases them slowly during the growing season (8). Humus in the sludge improves soil aggregation, structure, permeability, and moisture-retention capacity. Associated benefits are reduced crusting, leaching and erosion. On fine textured clayey soils, addition of humus may improve water infiltration over time as the soil structure improves (9).

Sandy soils or previously strip-mined lands may be particularly low in organic matter, and addition of sludge results in an increase in the organic matter content, thereby improving the water-holding characteristics, structure, and tilth (70). For example, at Elwood, Illinois, three years of successive sludge applications totalling about 75 tons per acre (168 tonnes/ha) resulted in soil organic matter increases to a depth of 12 inches (30.5 cm) on three soil types. Increases were greatest in Plainfield sand where organic matter increased in both the upper 12 inches (30.5 cm) and the 12- to 18-inch (30.5- to 45.7-cm) layers (8). In a study conducted at the Iona Island Sewage Treatment Plant in Vancouver, Canada, it was found that the organic matter content of dredged river sand increased from an initial 0.5% to 1.3 percent, 18 months after sludge addition at a loading rate of 6190 kg TKN/ha (68 tons or 61 tonnes dry solids/ha) (16).

Reports on sludge utilization to improve acid mine or strip mine spoils have been widely published (1,16-19,29,215). LEJCHER and KUNKLE (19) showed that sludge application on stripmine soils improved the physical conditions for germination and growth after 18 months. The pH of the soil increased as depicted in Table 9. These studies also indicate that sludge application on strip mine spoil must be at a level high enough to neutralize the acidity of the spoil to allow establishment of vegetation. At the end of the first growing season, the most heavily treated plot showed 90% vegetative cover (tall fescue and weeping lovegrass). Plots with lower treatment rates had less than 50% cover (1,17,19). The Metropolitan Sanitary District of Greater Chicago is also using sludge to transform Fulton Country, a once stripmined land about 200 miles (322 km) from Chicago, into a multiple-use acreage, to include farm land, forest, and conservation and recreation areas (18). A study conducted at Scranton, Pennsylvania, indicates that application of dried sludge is the most effective in promoting growth of tree seedlings on strip mine spoil material (17). All 3 loadings of 20, 40 and 80 tons per acre (44.8, 89.6 and 178.2 tonnes/ha) were found to be suitable.

MENZIES (20) has summarized the agricultural virtues of sewage sludge as

Table 9. Effect of Sludge Treatment on pH of Soil Within the Plots at the Palzo Tract, Illinois (19).

Treatment Rate (dry metric tons/hectare)	Plot Average Soil Surface pH
304	6.2
178	5.2
78	4.7
0	2.3

follows:

"it is a low-analysis, slow-release organic fertilizer valued mainly as a soil conditioner. It is not a particularly good buy if one has to pay what its costs to make it, transport it, and spread it. But if municipalities underwrite enough of these costs, if can be a good deal for agriculture and still be a cheap solution for the cities. Beyond this, and perhaps more important in the long run, the waste is recycled in a useful way back to the land from which it came".

3. CRITERIA AND STANDARDS FOR SLUDGE APPLICATION ON LAND.

According to TIETJEN (21), standards for waste utilization in crop production should provide reasonably high levels of public health protection as well as high levels of crop growth-promoting and soil-improving constituents in the waste. These levels provide the crop grower some certitude of economical success. Municipal wastes are suitable for crop production only if the content of major nutritive elements is low, and the content of toxic elements is still lower (21). Sewage sludges have a variable nature of chemical composition (22,23) and hence a sound sampling and analysis program is essential prior to formulating recommendations for rates of sewage sludge application on soils used for crop production. This is especially true when sludges produced from different cities is used for crop production due to their highly heterogenous nature.

A number of reports (1,4,8,17,24,25) attempt to establish standards for sludge application on land, but there is little agreement on allowable sludge application rates. For example, GARRIGAN (26) has shown that the maximum allowable annual sludge application rate for a typical sludge and application can vary from 0.6 to 20 ton/ac (1.3 to 44.8 tonnes/ha), depending on whom one believes. The lifetime application can vary from 9 to 408 ton/ac (20.2 to 914.2 tonnes/ha). Thus, as VESILIND (1) rightly points out, this variation illustrates the need for better information on the environmental impact of applying sludge to land.

Rate of sludge application are usually expressed as tons of dry solids per acre (or tonnes/ha) either on an annual basis or as the total lifetime load for the site. For a given disposal site, the maximum application rates depend on a number of factors: (i) Soil, (ii) Crops, (iii) Topography, (iv) Potential for water contamination, (v) Weather, (vi) Potential for odor production, and (vii) Method of application. The characteristics of the sludge include its concentration of (i) pathogenic organisms, (ii) heavy metals, (iii) nutrients (primary nitrogen), and (iv) toxins. The objective of land application standards is to incorporate these variables into a fair and enforceable statement (1). The maximum allowable application rates are calculated on the basis of a specific limiting parameter. The most common parameters are nitrogen and heavy metals. An attempt will be made here to describe the existing theories in this area.

3.1 Standards Based on Nitrogen

Nitrogen loading constitutes a major limiting factor for most land application systems (4). It is considered a potential pollutant because of the possible seepage of excess nitrate into the groundwater. This problem can be solved by adding the amount of nitrogen from sludge that is removed by the plants plus whatever is volatilized into the atmosphere or is lost due to denitrification, or considered an allowable increase in concentration in the groundwater. Organic nitrogen will mineralize gradually in the soil and SOMMERS and NELSON (25) suggest the following mineralization rates to estimate the amount of oganic N in sludge that will be released for plants to use:

(i) Twenty percent of the organic N during the first growing season following the sludge application, and

(ii) Three percent of the remaining, or residual, or organic N during the second, third and fourth growing season following application.

This percentage of sludge organic N added to the ammount of sludge inorganic N gives the total amount of N available to plants. The following two equations have been suggested (25) to calculate the appropriate rate of sludge application to agricultural land based on the N requirements of the crop to be grown:

available N/ton of dry sludge solids

$$= (N_i \times 20) + (N_o \times 4) \qquad \text{Eq. (1)}$$

where,

N_i = % inorganic N = (%NH_4-N) + (%NO_3-N)
N_o = % organic N
= (% Total N) - (% inorganic N)

sludge application rate (dry tons/acre)

$$= \frac{\text{crop N requirement - residual N}}{\text{lbs available N/ton sludge}} \qquad \text{Eq. (2)}$$

where,

crop N requirement = pound N/acre recommended.
residual N = pound N/acre released from sludge that had been applied in any of the previous three years.

The sludge application rate calculated by Equation 2 should be used when the sewage sludge is incorporated into the soil. When sludge is applied to the soil surface, the rate may need to be 1.5 times the rate calculated by Equation 2 to cover the N losses from denitrification and ammonia volatilization. The amount of residual N which will be available to plant from previous years sludge applications may be taken from Table 10 as suggested by SOMMERS and NELSON (25). These were calculated on the basis of having 3 percent of the remaining, or residual organic N released during the second, third and fourth growing season.

Table 10. Release of Plant-Available N During Sludge Decomposition in Soil (25).

Years after sludge application	Organic N content of sludge, %						
	2.0	2.5	3.0	3.5	4.0	4.5	5.0
	lb* residual N released per ton sludge added						
1	1.0	1.2	1.4	1.7	1.9	2.2	2.4
2	0.9	1.2	1.4	1.6	1.8	2.1	2.3
3	0.9	1.1	1.3	1.5	1.7	2.0	2.2

*1 kg = 2.2 lb
1 ton = 0.90718 tonnes

It should be noted, however, that in designing land application programs, the release of residual organic sludge N from previous applications should be calculated based on the locally available guidelines, wherever they exist.

In this context it may be relevant to mention that the P content of sludge is frequently high enough that, when using safe N limits as a guide for sludge application, higher P additions will be made than necessary for maximum crop growth. This may be assimilated by the soil's great capacity to retain P. Nevertheless excessive P additions from continued sludge applications may increase the possibility of leaching, particularly with the coarser soils. Regular soil fertility monitoring will ensure against such a problem. Plant growth problems due to excessive P are also not likely to occur where sludge application rates are based on the nutrient requirements of the crop and the related soil fertility tests (8).

3.2 Standards Based on Heavy Metals

Another criterion for determining suitable rates of sludge application to cropland is the heavy metal contents of sludges of which cadmium, copper, molybdenum, nickel, zinc and lead are of greatest concern. This is due to the fact that heavy metals applied in sludge (i) might be toxic to crops and/or (ii) might increase the heavy metal concentrations in edible crops enough to have harmful effects on animals and humans (8). At present there are no universally accepted standards for application based on heavy metals, although a number of researchers and governmental agencies have made suggestions.

(a) Zinc Equivalent (Z.E.)

CHUMBLEY (17) defined "Zinc Equivalent" (Z.E.) as a coefficient expressing a concentration of toxicants, weighted in terms of zinc (assuming copper and nickel to be 2 times and 8 times more toxic than zinc, respectively). According to him (17):

$$\text{Z.E. } \mu g/g = Zn^{+2}\ \mu g/g + 2(Cu^{+2}\ \mu g/g) + 8(Ni^{+2}\ \mu g/g) \qquad \text{Eq. (3)}$$

CHUMBLEY has proposed that no application of sludge be greater than 250 ppm zinc equivalent for soils with pH more than 6.5. The underlying principle is that copper seems to be twice as toxic to plants as zinc, and nickel about 8 times as toxic. The restriction on soil pH is because at a pH below 6.5, most metals are dissolved and are thus available to the plants. All standards for heavy metals suggested to date carry the restriction of pH greater than 6.5. If the pH of the soil (plus applied sludge) is less than 6.5, it must first be increased by lime addition before sludge is applied (1).

The zinc equivalent relationship is not a definitive one and should be used as a general guideline rather than a design relationship. The value of this relationship has decreased with the passage of time and the availability of newer information, as will be seen later.

(b) Guideline Based on Cation Exchange Capacity (CEC).

LEEPER (1,17) has recommended that the total toxic element load which could be added safely to unamended soils should not exceed 5% of the soil CEC at pH greater than 6.5. LEEPER'S generality is decidedly unsafe for general farming needs at pH values less than 6.5.

(c) Zinc:Cadmium Ratio.

It has been reported (8,211) that the rates of sludge application be limited by the ratio of Zn to Cd in the sludge. A Zn:Cd ratio of 100 or greater was suggested as a guideline for sludges to be considered safe for use on agricultural land. But recent research data show that many plants growing on nearly neutral to calcareous soils can tolerate high Zn levels and still show an increase in their Cd concentrations. Therefore Zn:Cd Ratio does not seem to be a very dependable criterion, especially where soil pH is maintained at 6.5 or above.

(d) USDA Guidelines.

The U.S. Department of Agriculture (USDA) has developed guidelines for cumulative metals addition in sludge to cropland, based on soil CEC (Table 11). These relate to privately owned farmland and the U.S. EPA suggests that higher application rates may be acceptable on publicly owned farmland or land dedicated to waste disposal, where adequate monitoring safe-guards are employed.

The zinc equivalent theory was based on limited data, although the best available at the time, and new information shows that toxicities of Zn, Ni and Cu are not necessarily additive. It is felt to greatly underestimate the amounts of metals which can be applied to soils of near-neutral to higher pH and it also does not apply to a broad range of plants. However, it has been used extensively in the past and may continue to find use in some quarters. The present trend is to use the USDA guidelines and it may be used extensively in the near future. The entire field of sludge limiting parameters is just developing and is in a state of flux (17).

3.3 Nitrogen Versus Potentially Toxic Element Loading

SOMMERS and NELSON (25) have outlined a methodology to calculate the sludge application rate to cropland based on the USDA guidelines (Table 11) for metal addition to crop and nitrogen requirement of the crop. The procedure can be explained by five steps (25):

Step 1. Obtain N requirement for the crop from Table 12 or obtain N fertilizer recommendation from soil analysis laboratory.

Table 11. Maximum Sludge Metal Addition to Farmland (17, 134). (Over the Site Lifetime)

Metal	Maximum Metal Addition (kg/ha) to Soil with a C.E.C. (meq/100 g) of:		
	Less than 5	5-15	Greater than 15
Pb	500	1000	2000
Zn	250	500	1000
Cu	125	250	500
Ni	50	100	200
Cd	5	10	20

Step 2. Calculate tons of sludge needed to meet crop's N requirement.

a. Available N in sludge

% Inorganic N (N_i) = (% NH_4-N) + (% NO_3-N)
% Organic N (N_o) = (% total N) - (% inorganic N)

i) Surface applied sludge
lb. available N/ton sludge = (%NH_4-N × 10) + (% NO_3-N × 20) + (% N_o × 4)

ii) Incorporated sludge
lb. available N/ton sludge = (% NH_4-N × 20) + (% NO_3-N × 20) + (% N_o × 4)

b. Residual sludge N in soil
If the soil has received sludge in the past 3 years, calculate residual N from Table 10.

c. Annual application rate

i) $$\text{Tons sludge/acre} = \frac{\text{crop N requirement - residual N}}{\text{lb. available N/ton sludge}}$$

ii) $$\text{Tons sludge/acre} = \frac{\text{2 lb. Cd/acre}}{\text{ppm Cd} \times .002}$$

iii) The <u>lower</u> of the two amounts is applied.

Step 3. Calculate total amount of sludge allowable.

a. Obtain maximum amounts of Pb, Zn, Cu, Ni, and Cd allowed for CEC of the soil from Table 11 in lb/acre.

b. Calculate amount of sludge needed to exceed Pb, Zn, Cu, Ni, and Cd limits, using sludge analysis data.

Metal:

Pb: $\text{Tons sludge/acre} = \dfrac{\text{lb. Pb/acre}}{\text{ppm Pb} \times .002}$

Zn: $\text{Tons sludge/acre} = \dfrac{\text{lb. Zn/acre}}{\text{ppm Zn} \times .002}$

Cu: $\text{Tons sludge/acre} = \dfrac{\text{lb. Cu/acre}}{\text{ppm Cu} \times .002}$

Ni: $\text{Tons sludge/acre} = \dfrac{\text{lb. Ni/acre}}{\text{ppm Ni} \times .002}$

Cd: $\text{Tons sludge/acre} = \dfrac{\text{lb. Cd/acre}}{\text{ppm Cd} \times .002}$

(Note: Sludge metals should be expressed on a dry-weight ppm mg/kg basis)

The lowest value is chosen from the above five calculations as the maximum tons of sludge per acre which can be applied.

Step 4. Calculate amount of P and K added in sludge.

Tons of sludge × % P in sludge × 20 = lb. of P added
Tons of sludge × % K in sludge × 20 = lb. of K added

Step 5. Calculate amount of P and K fertilizer needed.

(lb. P recommended for crops)* - (lb. P in sludge) = lb. P fertilizer needed

(lb. K recommended for crops)* - (lb. K in sludge) = lb. K fertilizer needed

3.4 Nitrogen -- Major Limiting Factor in Operation of Site

The land area required for a sludge land application system depends on many factors related to the characteristics of the soil, climate, sludge, and crop, and should be evaluated using site specific information. The application rate of water organics, nutrients, potentially toxic elements, and salts significantly affect the required land area. When evaluating the required land area, the land area for each potentially limiting parameter should be determined. That parameter which requires the largest land area to avoid environmental problems becomes the limiting parameter. Thus "limiting parameter principle" states that the design land area shall be no less than that allowed by the limiting environmental parameter (4,97).

A representation of computed land area requirements based on various factors is shown in Fig. 10. Based on the relative land areas required, nitrogen

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* P and K recommendations based on soil tests for available P and K. Fertilizer recommendations can be obtained from soil analysis laboratory.

Table 12. Annual Nitrogen, Phosphorus, and Potassium Utilization by Selected Crops* (25).

Crop	Yield	Nitrogen	Phosphorus	Potassium
		lb. per acre		
Corn	150 bu.	185	35	178
	180 bu.	240	44	199
Corn silage	32 tons	200	35	203
Soybeans	50 bu.	257†	21	100
	60 bu.	336†	29	120
Grain sorghum	8,000 lb.	250	40	166
Wheat	60 bu.	125	22	91
	80 bu.	186	24	134
Oats	100 bu.	150	24	125
Barley	100 bu.	150	24	125
Alfalfa	8 tons	450+	35	398
Orchard grass	6 tons	300	44	311
Brome grass	5 tons	166	29	211
Tall fescue	3.5 tons	135	29	154
Bluegrass	3 tons	200	24	149

*Values reported above are from reports by the Potash Institute of America and are for the total above-ground portion of the plants. Where only grain is removed from the field, a significant proportion of the nutrients is left in the residues. However, since most of these nutrients are temporarily tied up in the residues, they are not readily available for crop use. Therefore, for the purpose of estimating nutrient requirements for any particular crop year, complete crop removal can be assumed.

†Legumes get most of their nitrogen from the air, so additional nitrogen sources are not normally needed.

1 bu = 35.2 ℓ
1 lb per acre = 1.12 kg per ha
1 ton = 0.90718 tonnes

is most often the controlling design parameter. When the waste is applied over the area required for nitrogen, an added degree of safety occurs in terms of the loading rates of other constituents. For example, if the nitrogen -area requirement is 15 times that for toxics, this reflects a 15-fold safety factor in the application area for toxics (4).

3.5 Other Criteria

Besides nutrients and toxic elements guidelines are also based on topography, permeability of soil and proximity of watercourses. For example, application of sludge is recommended only on fairly level surfaces to prevent surface water contamination. BELL (1) has suggested that the minimum acceptable soil permeability is 10 cm/sec (0.015 in./hr) in the U.S. According to him slopes greater than 3% should not be used if the soil permeability is less than 10 cm/sec (0.15 in./hr).

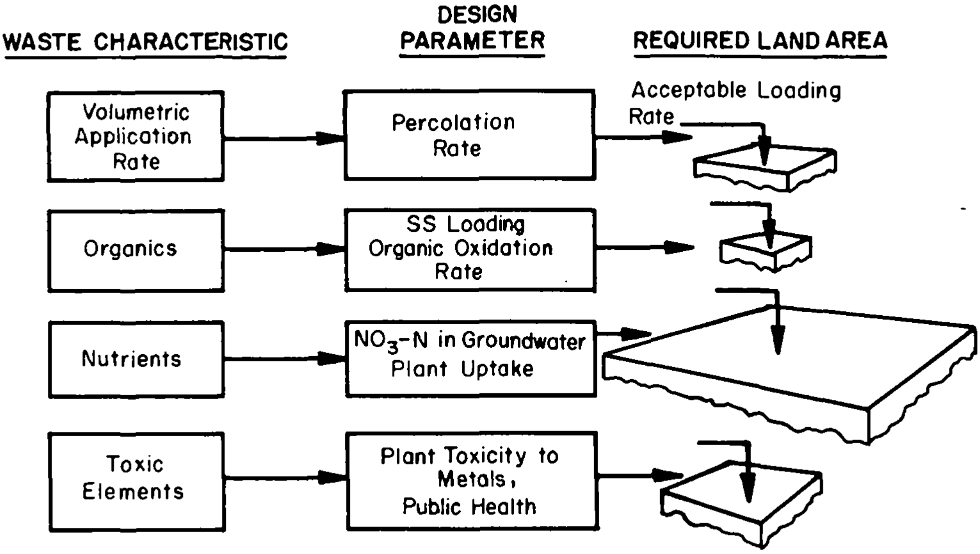


Figure 10. Example of Relationships between Waste Constituents and Limiting Design Parameters for Land Application Systems (4).

Each state or locality should establish its own guidelines based on its climate, soil characteristics, crop to be grown, nature of the wastes, legal requirements, etc., so that land application of sludge is compatible with the local environment. In the U.S. many states have their own set of guidelines (27, 28) in addition to the EPA recommendations (9) for application of sludge to agricultural soils based on crop studies. The EPA recommendations are the following:

(i) Maintain a pH of 6.5 or greater for the soil-sludge mixture

(ii) Total cumulative metal loading should not exceed values given in Table 11

(iii) Select crop species that do not take up cadmium

(iv) Available nitrogen from applied nitrogen should not exceed crop needs

(v) Monitor sludge, soil, and crop adequately.

In the U.S., the application rates criteria for sludge application on land have been well clarified by the U.S. Environmental Protection Agency in the criteria and regulations that it has developed for solid waste disposal facilities and practices (178). The Agency believes that even food-chain land application practices which comply with the criteria mentioned below will pose no reasonable probability of adverse effects on public health or the environment. The main regulations dealing with food-chain crops may be interpreted for sludge as given below. The logic for these regulations is well discussed in the Federal Register (178).

(a) Cadmium.

A facility or practice concerning application of sludge to within one meter (three feet) of the surface of land used for the production of food-chain crops shall not exist or occur, unless in compliance with all requirements of paragraph (a)(1) or (2):

(1) (i) The pH of the sludge and soil mixture is 6.5 or greater at the time of each sludge application, except for sludge containing cadmium at concentrations of 2 mg/kg (dry weight) or less.

(ii) The annual application of cadmium sludge does not exceed 0.5 kilograms per hectare (kg/ha) on land used for production of tobacco, leafy vegetables or root crops grown for human consumption. For other food-chain crops, the annual cadmium application rate does not exceed the values set out in Table 13.

(iii) The cumulative application of cadmium from sludge does not exceed the levels in Table 14. For soils with a background pH of less than 6.5, the cumulative cadmium application rate does not exceed the levels in Table 15, provided the pH of the sludge and soil mixture is adjusted to and maintained at 6.5 or greater whenever food-chain crops are grown.

(2) (i) The only food-chain crop produced is animal feed.

(ii) The pH of the sludge and soil mixture is 6.5 or greater at the time of sludge application or at the time the crop is planted whichever occurs later, and this pH level is maintained whenever food-chain crops are grown.

(iii) There is a facility operating plan which demonstrates how the animal feed will be distributed to preclude ingestions by humans. The facility operating plan describes the measures to be taken to safeguard against possible health hazards from cadmium entering the food chain, which may result from alternative land uses.

(iv) Future property owners are notified by a stipulation in the land record or property deed which states that the property has received sludge at high cadmium application rates and that food-chain crops should not be grown, due to possible health hazard.

(b) Polychlorinated Biphenyls (PCBs).

Sludges containing concentrations of PCBs equal to or greater than 10 mg/kg (dry weight) is incorporated into the soil when applied to land used for producing animal feed, including pasture crops for animals raised for milk. Incorporation of the sludge into the soil is not required if it is assured that the PCB content is less than 0.2 mg/kg (actual weight) in animal feed or less than 1.5 mg/kg (fat basis) in milk.

The preapplication requirements in the U.S., as related to diseases, fall into two categories in general (178) : (i) Processes to significantly reduce pathogens, and (ii) Processes to further reduce pathogens.

(A) Processes to Significantly Reduce Pathogens.

(i) Aerobic digestion: The process is conducted by agitating sludge with air or oxygen to maintain aerobic conditions at residence times ranging from 60 days at 15 degrees Centigrade to 40 days at 20 degrees Centigrade, with a volatile solids reduction of at least 38 percent.

Table 13. Annual Cadmium Application Rate (178).

Time period	Annual Cd application rate (kg/ha)
Present to June 30, 1984	2.0
July 1, 1984 to Dec. 31, 1986	1.25
Beginning Jan. 1, 1987	0.5

Table 14. Maximum Cumulative Cadmium Application Rate (178).

Soil cation exchange capacity (meq/100 g)	Maximum cumulative application (kg/ha)	
	Background soil pH <6.5	Background soil pH ⩾6.5
<5	5	5
5-15	5	10
>15	5	20

Table 15. Maximum Cumulative Cadmium Application for Soils with Background pH Less than 6.5 (178).

Soil cation exchange capacity (meq/100 g)	Maximum cumulative application (kg/ha)
<5	5
5-15	10
>15	20

(ii) Air Drying: Liquid sludge is allowed to drain and/or dry on under-drained sand beds, or paved or unpaved basins in which the sludge is at a depth of nine inches (23 cm). A minimum of three months is needed, two months of which temperatures average on a daily basis above 0 degrees Centigrade.

(iii) Anaerobic digestion: The process is conducted in the absence of air at residence times ranging from 60 days at 20 degrees Centigrade to 15 days at 35 to 55 degrees Centigrade with a volatile solids reduction of at least 38 percent.

(iv) Composting: Using the within-vessel, static aerated pile or windrow composting methods, the sludge is maintained at minimum operating conditions of 40 degrees Centigrade for 5 days. For four hours during this period the temperature exceeds 55 degrees Centigrade.

(v) Lime stabilization: Sufficient lime is added to produce a pH of 12 after 2 hours of contact.

(vi) Other methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

(B) Process to Further Reduce Pathogens.

(i) Composting: Using the within-vessel composting method, the sludge is maintained at operating conditions of 55 degrees Centigrade or greater for three days. Using the static aerated pile composting method, the sludge is maintained at operating conditions of 55 degrees Centigrade or greater for three days. Using the windrow composting method, the sludge attains a temperature of 55 degrees Centigrade or greater for at least 15 days during the composting period. Also, during the high temperature period, there will be a minimum of 5 turnings of the windrow.

(ii) Heat drying: Dewatered sludge cake is dried by direct or indirect contact with hot gases, and moisture content is reduced to 10 percent or lower. Sludge particles reach temperatures well in excess of 80 degrees Centigrade, or the wet bulb temperature of the gas stream in contact with the sludge at the point where it leaves the dryer is in excess of 80 degrees Centigrade.

(iii) Heat treatment: Liquid sludge is heated to temperatures of 180 degrees Centigrade for 30 minutes.

(iv) Thermophilic aerobic digestion: Liquid sludge is agitated with air or oxygen to maintain aerobic conditions at residence times of 10 days at 55-60 degrees Centigrade, with a volatile solids reduction of at least 38 percent.

(v) Other methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

In addition, any of the processes listed below, if added to the processes described in Section (A) above, further reduce pathogens. Because the processes listed below, on their own do not reduce the attraction of disease vectors, they are only add-on in nature.

(vi) Beta ray irradiation: Sludge is irradiated with beta rays from an accelerator at dosages of at least 10 megarad at room temperature (ca. 20 degrees Centigrade).

(vii) Gamma ray irradiation: Sludge is irradiated with gamma rays from certain isotopes, as Cobalt 60 and Cesium 137, at dosages of at least 1.0 megarad at room temperature (ca. 20 degrees Centigrade).

(viii) Pasteurization: Sludge is maintained for at least 30 minutes at a minimum temperature of 70 degrees Centigrade.

(ix) Other methods: Other methods or operating conditions may be acceptable if pathogens are reduced to an extent equivalent to the reduction achieved by any of the above add-on methods.

Based on these two processes, regulations to protect against diseases have been drawn up as follows (178):

(a) Disease Vectors.

The facility or practice shall not exist or occur unless the on-site population of disease vectors is minimised through the periodic application of cover material or other techniques as appropriate so as to protect public health.

(b) Sewage Sludge.

A facility or practice involving disposal of sewage sludge shall not exist or occur unless in compliance with the following:

(i) Sewage sludge that is applied to the land surface or is incorporated into the soil is treated by a Process to Significantly Reduce Pathogens prior to application or incorporation. Public access to the facility is controlled for at least 12 months, and grazing by animals whose products are consumed by humans is prevented for at least one month. (These provisions do not apply to sewage sludge disposed of by a trenching or burial operation).

(ii) Sewage sludge that is applied to the land surface or is incorporated into the soil is treated by a Process to Further Reduce Pathogens, prior to application or incorporation, if crops for direct human consumption are grown within 18 months subsequent to application or incorporation. Such treatment is not required if there is no contact between the sludge and the edible portion of the crop; however, in this case the sludge is treated by a Process to Significantly Reduce Pathogens, prior to application; public access to the facility is controlled for at least 12 months; and grazing by animals whose products are consumed by humans is prevented for at least one month. If crops for direct human consumption are not grown within 18 months of application or incorporation, the requirements of the above paragraph (b) (i) apply.

In the U.S., any owner or operator of a publicly owned treatment works must comply with the above-mentioned regulations when disposing of sludge on the land. Developing countries may also impose similar regulations to ensure that land disposal of sludge is an environmentally safe method of disposal.

Shortly after promulgation of the above mentioned criteria in the U.S., some food processors raised a series of questions concerning the perceived safety and legality of food crops grown on sludge-amended soils, and procedures necessary to properly manage the application of sewage sludge to land used to grow fruits and vegetables. In response, the U. S. Environmental Protection Agency, the U. S. Food and Drug Administration and the U. S. Department of Agriculture collaborated in the development of a recent statement of the U.S. federal policy and guidance dealing with land application of sludge for production of fruits and vegetables, which is structured upon the above mentioned criteria (229). This is the document now being used in the U.S. for guidance when sludge is applied to agricultural land for the growth of food chain crops.

4. DESIGN PROCEDURES FOR LAND APPLICATION OF SLUDGE.

4.1 Design Objectives

The main objectives of land application of sludges are: (i) the disposal of waste products or residues, and (ii) the use of nutrients and organic matter to fertilise crops and reclaim soil (13). The first case views sludge merely as a waste to be dumped or simply disposed, whereas in the second case, sludge is considered as a resource that can be used as a fertilizer, a soil conditioner, or (for liquid sludge) a source of irrigation. The latter land treatment system uses and conserves the resources in wastes (water, nutrients, organic matter) to enhance the soil and crop production rather than simply dispose of the wastes (13,30).

In designing an acceptable sludge application system, care should be taken to see that there is no detrimental impact on the environment (air, water, or soil), while using the best available equipment to handle and apply the sludge on the land, in an economical manner, with good management practices such as uniform application and minimum nuisance (31).

4.2 Factors Affecting Sludge Application Systems and Equipment

The chief factors that affect the sludge application systems and equipment are (i) the characteristics of the sludge, (ii) the amount of sludge, (iii) the site characteristics, and (iv) the applicaton schedule. Among the sludge characteristics, sludge solids content plays the most significant role in defining the application systems and equipment. The quantity of the sludge produced is a function of the size of the city. Among the site characteristics that affect sludge land application system, the soil type, topography, type of cover crops and the acreage are the most important. Soil and slope of the site are not altered to fit a certain treatment method; rates of waste application are adjusted to fit the site characteristics. Again, the ability of the soil structure to maintain its integrity as well as permeability under saturated conditions limits the application system selected. The cover crop at the site has direct bearing on which application system to select: surface irrigation of liquid sludge is suited to close-growing crops, ridge and furrow systems for row crops and sprinkler irrigation can be adapted to all vegetative covers. The weather, trafficability and rotations are other factors to be considered in the selection and designing of sludge application systems (17,32).

Treatment (storage), transport, and application are three interdependent phases in the handling of sludges for land application. For example, the extent of treatment will affect the mode of transportation (i.e. vacuum filtered sludge will have to be hauled as solid). Similarly, in the case of stabilized sludge, soil incorporation should be undertaken to avoid nuisance. Storage of sludge during inclement weather or adverse conditions will have to be thought of as a vital part of the total handling system, e.g. freezing weather or wet ground. The type of transportation and equipment depends on the form in which sludge will be applied to the soil, i.e. as a slurry (liquid), semi-solid, or solid (cake). Table 16 indicates a range of solids content and handling characteristics (31).

4.3 Transport of Sludge

Selection of the transportation systems will depend on the sludge production rate i.e. the quantity, distance to site, proximity of application

Table 16. Sludge Solids Content and Handling Characteristics (31).

Type	Solids Content	Handling Methods
Liquid	1-10%	Gravity flow, pump, tank transport
Semi-Solid ('wet' solids)	8-30%	Conveyor, auger, truck transport (Water-tight box)
Solid ('dry' solids)	25-80%	Conveyor, bucket, truck transport (box)

area to waterway, railway, or highway, whether application will be seasonal or year round, and the life of the application area. Alternate modes of transport for liquid and solid sludges are listed in Table 17. In the case of large cities producing large quantities of sludge, pipeline, barge, or rail tank car may be used economically and may be the best choice from the viewpoint of management. But in the case of small cities or small communities, the use of truck is the best choice and provides flexibility. For long hauling distances, tank trucks may be used for hauling over the highway and then the sludge may be transferred to either a high flotation tank truck or tank wagon for field spreading. Year-round application by truck or tank wagon necessitates the use of flotation tires to allow field travel over soft ground. Another advantage of tank truck is that it provides flexibility in locating land application areas, scheduling hauling, and enabling direct application, if soil conditions permit (31).

4.4 Storage of Sludge

Storage will have to be provided at some stage in the system for handling sludge. The two alternatives are at the treatment facility or at the land application site. It would normally be best to provide storage at the treatment facility except in cases where space is limiting at the treatment site (large cities). Storage is important for the following reasons: (i) to prevent hindrance in transportation by fluctuations in the sludge output at the treatment site, (ii) to ensure constant supply for land application if a breakdown occurs in the transportation, (iii) to withhold application during inclement weather or when adverse soil conditions at the application area prevent immediate application.

Short time storage may be provided in the digester or aeration tanks, but for long term storage, a tank or lagoon is normally necessary. Public acceptance is an important requisite for a successful land application system and this may be ensured by providing the storage tanks or lagoons at the treatment sites rather than the application site. One problem that may be envisaged with sludge storage units is the settling of suspended solids. Hence the agitation of sludge in storage units is necessary before transporting. Another solution is to minimize the number of storage events in the handling system (31,207).

Table 17. Transport Modes for Sludges (31).

Type	Characteristics
LIQUID SLUDGE	
Rail Tank Car	100 wet tons (24,000 gal.) capacity; suspended solids will settle while in transit.
Barge	Capacity determined by waterway; Chicago has used 1,200 wet tons (290,000 gal.) barges.
Pipeline	Need minimum velocity of 1 fps to keep solids in suspension; friction decreases as pipe diameter increases (to the fifth power); buried pipeline suitable for year-round use.
Vehicles	
Tank Truck	Capacity--up to maximum load allowed on road. Can have gravity or pressurized discharge. Field trafficability can be improved by using flotation tires.
Farm Tank Wagon and Tractor	Capacity--800 to 3,000 gallons. Principal use would be for field application.
SEMI-SOLID OR SOLID SLUDGE	
Rail Hopper Car	Need special unloading site and equipment for field application.
Truck	Commercial equipment available to unload and spread on ground; need to level sludge piles if dump truck is used.

4.5 Application Methods and Equipment

The selection of application systems and equipment depends on: (i) the form of the sludge (liquid, semi-solid, or solid), (ii) the quantity, (iii) the areal application rate, (iv) whether a yearly application to the same area or one application in several years is followed, (v) whether the application is seasonal or year-round, (vi) topography of the area, and (vii) the time of year (31).

There has been a lot of concern about surface water pollution with organic materials, nutrients, heavy metals and disease organisms in sludge. Hence some states in the U.S. require berms and/or diversions to be formed, requiring land shaping in order to prevent run-off (31,33).

It may be mentioned that application of sludge to land in the liquid state is attractive because of its simplicity. It does not warrant dewatering processes and inexpensive liquid-transfer systems can be used. On the other hand, application of dewatered sludge has its own advantage. It is similar to an application of semisolid animal manure and so private farmers can handle application on their lands with their own equipment (13).

There are two modes of application of sludge to land (i) surface and (ii) sub-surface (soil incorporation). The latter is useful to control odors and pathogens in raw or partially stabilized sludge and to produce a good public image where large quantities of digested sludge are being applied. WHITE (31) has listed methods and equipment which can be used for surface or subsurface application of liquid and semisolid sludge and these are shown in Table 18.

Surface application of liquid and semisolid sludge can be done by two general methods (i) Irrigation (consisting of sprinkling and ridge-and-furrow methods), and (ii) Tank vehicle.

(i) Irrigation.

The two modes of irrigation are (a) sprinkling and (b) ridge-and-furrow methods. Experience has indicated that a fixed irrigation, in lieu of using portable pipe is easier to manage (31). Hence, in a case where sludge is applied regularly, irrigation is better suited. It is also possible to include sludge with a treated wastewater irrigation application system.

(a) Sprinkling.

Sprinklers can be either fixed (stationary) or portable (travelling) (1,13) and they have been designed to handle solids without clogging. Nowadays pressurized spraying is done through "big gun" sprinklers having nozzle diameters of about 2 cm (0.75 in.) (1,17). The benefits of spraying are the following (13) : (i) reduced operating labor, (ii) less land preparation, (iii) use on a wide variety of plants, (iv) fixed units can be highly automated, although operator attention is required to set portable sprinkler systems, (v) sprinklers can operate satisfactorily on land too rough or wet for tank trucks or injection equipment, and (vi) it can be used throughout the growing season. Some disadvantages of sprinkling include (13):(i) power costs of high pressure pumps, (ii) contact of sludge with all parts of the crop, (iii) possible foliage damage to sensitive crops, and (iv) the potential for aerosol pollution from entrained pathogens. Although the problem of sludge contact with crops will limit the types of crop that can be grown (as will be seen later), the aerosol problem can be controlled by buffer zones, low-pressure sprinkler, and operational control to avoid sprinkling on windy days. Only well screened sludge should be used for spraying, otherwise there will be clogging of the sprinkler head (34).

(b) Ridge-and-Furrow Methods.

The second method of irrigating sludge on land is by means of ridges and furrows. The topographical and seasonal requirements for this method can be seen in Table 18.

Ridge-and-furrow sludge application on land is basically the same operation as ridge and furrow crop irrigation (13). Sludge is applied in the furrows between row crops, irrigating and fertilizing the soil. This system of application has the following advantages (13):(i) simplicity of equipment, and (ii) flexibility of use at existing sites.

As with other methods of sludge application on land, ridge-and-furrow method is not without its drawbacks. These include the following (13): (i) settling of solids at the heads of the furrows, (ii) need for well-prepared sites with proper gradients, and (iii) ponding of sludge in the furrows.

Table 18. Application Methods and Equipment for Liquid and Some Semi-Solid Sludges (31).

Method	Characteristics	Topographical and Seasonal Suitability
SURFACE APPLICATION		
Irrigation		
Spray (Sprinkler)	Large orifice required on nozzle; large power and lower labor requirement; wide selection of commercial equipment available; sludge must be flushed from pipes when irrigation completed.	Can be used on sloping land; can be used year-round if the pipe is drained in winter; not suitable for application to some crops during growing season; odor (aerosol) nuisance may occur.
Ridge and furrow	Land preparation needed; lower power requirements than spray.	Between 0.5 and 1.5% slope depending on percent solids; can be used between rows of crops.
Overland flow	Used on sloping ground with vegetation with no runoff permitted; suitable for emergency operation; difficult to get uniform areal application.	Can be applied from ridge roads.
Tank Truck	Capacity 500 to more than 2,000 gallons; larger volume trucks will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.
Farm Tank Wagon and Tractor	Capacity, 500 to 3,000 gallons; larger volume will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.

Table 18. (continued)–Application Methods and Equipment for Liquid and Some Semi-Solid Sludges (31).

Method	Characteristics	Topographical and Seasonal Suitability
SURFACE APPLICATION		
Flexible irrigation hose with plow furrow or disc cover	Use with pipeline or tank truck with pressure discharge; hose connected to manifold discharge on plow or disc.	Tillable land; not usable on wet or frozen ground.
Tank truck with plow furrow cover	500-gallon commercial equipment available; sludge discharged in furrow ahead of plow mounted on rear of 4-wheel-drive truck.	Tillable land; not usuable on wet or frozen ground.
Farm tank wagon and tractor		
plow furrow cover	Sludge discharged into furrow ahead of plow mounted on tank trailer--application of 170 to 225 wet tons/acre; or sludge spread in narrow band on ground surface and immediately plowed under-application of 50 to 125 wet tons/acre.	Tillable land; not usuable on wet or frozen ground.
Subsurface injection	Sludge discharged into channel opened by a tillable tool mounted on tank trailer; application rate 25 to 50 wet tons/ acre; vehicles should not traverse injected area for several days.	Tillable land; not usable on wet or frozen ground.

1 acre = 0.405 ha
1 ton/acre = 2.24 Mg/ha

(ii) Tank Truck Spreading.

Communities of 10,000 to 15,000 population have utilized tank trucks to apply their sludge on farmland (31). This is a common method in which tank trucks with capacities ranging from 3.8 to 7.6 cubic meters (1,000 to 2,000 gal.) have been used (13). As the truck is driven across the field, sludge is spread from a manifold on the rear of the truck. Control of application rates have been achieved by valving on the manifold or by varying the speed of the truck as the hydraulic head decreases (1). A spray apparatus may be mounted on the truck for achieving a wider application area by each pass. The system can be refined so that larger tank trucks can operate from a network of roads at the application site by means of pressurized spraying from the side of the truck, which may be important in an emergency.

The principle advantages of a tank truck system are (13,31):(i) low capital investment, (ii) ease of operation, (iii) flexibility of system in that a variety of application sites can be served, such as pastures, golf courses, farmland, and athletic fields, and (iv) year round application can be performed by selecting sodded fields for application during wet conditions. Disadvantages include (13):(i) wet weather problems, and (ii) high operating cost of the sludge haul. Special flotation tires partially solves the wet weather problem. Otherwise storage or wet weather alternatives must be available. Repeated tank truck traffic may reduce crop yields due to damage to soil structure by compaction (high bulk density, reduced infiltration) (13). Nevertheless the success of this method is brought out by a study conducted in Ohio, U.S.A., in which it was revealed that the vast majority of landspreading communities are using tank trucks as their principal method of disposal (35).

Soil incorporation (subsurface application) should be designed into the application system where there is a possbility of public nuisance from sludge application. Wastes with solids concentration of upto 8 percent have been successfully disposed of using subsurface infection (36).

The principle used in sludge incorporation is to cut a furrow, deliver sludge into the furrow, and cover the sludge, all in one operation. One modification to this is an injection system in which the sludge is injected beneath the surface without turning over the soil. Another practice is to trench or plow sludge into the soil. The chief advantages of sludge incorporation are : (i) the immediate mixing of sludge and soil, thereby eliminating the odor and vector problems that can arise from ponding sludge (13), and (ii) greater nitrogen use efficiency (31). The principle disadvantages include (13):(i) its seasonal limitations, and (ii) handling procedures. It is difficult to sequence sites throughout the year as application can be made only prior to the growing season or on noncultivated land. This method also necessitates a tank truck or trailer to be part of the application system and hence wet-weather operation is limited. This technique also warrants a larger power unit to perform both tillage and application simultaneously (31).

Land application of sludge in a solid form may be the best option where equipment to dewater the sludge into a cake is currently available at the waste treatment plant (31). Economics has bearing on dewatering if the sludge has to be transported a long distance. WHITE (13) has outlined the methods and equipment for applying sludge to the soil in the solid form and these are depicted in Table 19. As seen in the table, the method usually used is spreading by a tractor and disking in the sludge. Dewatered sludge can also be transported by truck, reslurried at the site, and the liquid sludge applied as mentioned above (1). Spreading method is generally preferred over the piling or windrowing is order to facilitate normal farm tillage operations and cropping.

Whatever be the method of sludge application, caution should be exercised in the planning and running of such systems. Although there is a large body of practical experience, method of application has received little scientific investigation. Because of the reactions of nutrients, heavy metals, and pathogenic organisms in sludge with soils and plants, one would expect large differences in the effect on plant growth and persistence of pathogens depending on whether sludge is left on the soil surface or turned under. There is also the danger of surface water pollution due to runoff. Hence, regular monitoring is

Table 19. Methods and Equipment for Application of Semi-solid and Solid Sludges (31).

Method	Characteristics
Spreading	Truck-mounted or tractor-powered box spreader (commercially available); sludge spread evenly on ground; application rate controlled by over-the-ground speed; can be incorporated by discing or plowing.
Piles or windrows	Normally hauled by dump truck; spreading and leveling by bulldozer or grader needed to give uniform application; 4 to 6-inch layer can be incorporated by plowing.
Reslurry and handle as in Table 18.	Suitable for long hauls by rail transportation.

required to gauge if there is any danger of pollution to surface or groundwater and it is also necessary to relate crop growth and yield to method of application and to establish the optimum method and loading for a particular locality and crop.

It is evident from this discussion that sludge application requires special equipment. Many companies in the U.S. (37) and other countries have started manufacturing these specialized equipment due to the revival of interest in sludge land disposal. As we have seen earlier, sludge slurries may be sprayed, spread through outlets mounted on a portable tank, or placed under the soil surface by special plow attachments (17).

Gun sprinklers, travelling or stationary, can handle sewage sludge or liquid animal manure slurries of around 15% solids. Specifications for this application include a nozzle diameter of at least 3/4 inch (1.9 cm) and minimum sprinkler pressure of 70 to 80 psi. If possible, it may be advisable to pump wastewater or water from another source (other than a potable supply) through the gun sprinkler following each sludge application. This will wash solids off foliage (some problems have been noted with crop burning due to high chemical concentrations in slurries), clean out the pipe, and clean the sprinkler and the external surfaces nearby. If wastewater is not available, a farm pond is an excellent source if auxiliary pumping equipment can be used (17).

Tankwagons for sludge application are, as mentioned before, normally 1,000 to 2,000 gallons capacity, with some being over 5,000 gallons. Tanks designed to be pulled through tilled fields use oversize tires. Wagons can be economical for hauling wastes to distant fields, which would be costly to use with irrigation systems. Curves of number of trips necessary to dispose of given volumes of wastes were developed by PETERSON (17) (Fig. 11) and these aid in economic assessment of this alternative. Tankwagons can have outlets, usually consisting of a manifold with deflectors on the openings for direct surface application (17).

For subsurface application, subsurface plow spreaders can be used. Shallow injection with good mixing of sludge and soil produces rapid drying and maintains aerobic conditions. Injection depths of no more than 4 to 6 inches

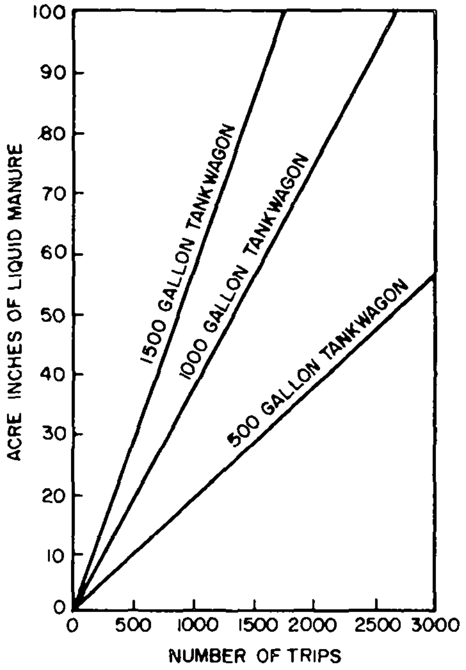


Figure 11. Economic Analysis of Sludge Application Systems may be Related to the Number of Trips Necessary to Apply a Certain Volume with Various Sizes of Tank Wagons (17).

(10.2 to 15.2 cm) should be used. Tractors pulling these chisel plow systems may also be fitted with a sludge tank, which must be of a limited size, thus maximizing sludge transport problems. Systems for sludge injection which use the same flexible hose used with traveling "big gun" sprinklers are commercially available. The hose connects a large mobile tank with the tractor plow attachment. In this way trips between sludge source and field with the tankwagons are minimized, and operating costs reduced.

4.6 Sludge Application or Loading Rates

The sludge application rate depends on sludge characteristics, soil types, climate, and crop to be grown. Sludge nutrient content, particularly the nitrogen and trace element content are usually limiting factors in land application. Establishing loading rates based on these criteria have been outlined in the foregoing section (Section 3). Infiltration and water retention are influenced by the physical properties of the soil. Precipitation also affects the hydraulic characteristics of the soil. Another factor which affects the sludge application rate on land is the performance of application equipment in wet or cold weather (13).

However, it much be emphasized that there is little agreement on allowable sludge application rates. As mentioned before, GARRIGAN (26) has shown that the maximum allowable annual sludge application rate for a typical sludge and application can vary from 0.6 to 20 ton/ac (1.3 to 44.8 tonnes/ha). The lifetime

Table 20. Sludge Loading Vary Widely, Yet All Have Been Reported as Causing "No Significant Effect" on Vegetation (38).

Authority	Recommended Load Rate
National Swedish Board of Health and Welfare (Emmelin, 1973)	0.43 short ton/acre-yr
Hinesly (1972)	27 short tons/acre-yr (5-yr average)
Metropolitan Sanitary District of Greater Chicago (Lyman, et al., 1972)	"similar to Hinesly"
Le Riche (1968) (England)	29 short tons/acre-yr (19-yr average)

1 acre = 0.405 ha
1 ton = 0.90718 tonnes

Table 21. Examples of Sludge Application Rates on Agricultural Land (39).

Source	*Quantity/acre*	*Type of Land*
East Kilbride	6000 gal	Pasture
Rye Meads	5000 gal @ 5% solids	Pasture & Arable
Maple Lodge	10,000 gal ± @ 4% solids	Pasture & Arable
Uppsala	4 to 15 tons * (dry matter)	Arable
Mogden	33 tons (wet sludge)	Arable
Berkley	80 tons (dried) 6.4% Moisture	Arable

*Recommendation of the Swedish National Board of Health and Welfare.

± Recommended application per annum.

1 ton = 0.90718 tonnes

application can vary from 9 to 408 ton/ac (20.2 to 914.2 tonnes/ha) (1,26). Some rates used in the U.S. and Europe are summarized in Tables 20 and 21. LOEHR (27) points out that application rates of 0.5 to 50 tons dry solids/acre/year (1.12 to 112.04 tonnes/ha) have generally been used where the disposal was in conjunction with field crops. Higher application rates have been used for infrequent loadings to reclaim sandy soils. According to him, rates of application are dependent upon whether it is being integrated into a crop production system or primarily for disposal (27). In Great Britain, stabilized sludges with solids content between 2 and 5 percent have been used successfully with loading rates less than 5 tons of dry solids per acre per year (40). Models have also been used to determine application rates for municipal sewage sludges. One such model developed by LOFTIS and WARD (41) incorporated economic information and a soil nitrogen balance. Based on input conditions for Boulder, Colorado, the model suggests an average optimal annual application rate of 10.5 tonnes/ha for subsurface injection of municipal sewage sludge (41).

This great variation in application rates for sewage sludge illustrates the difficulty in evaluating the environmental impact of sludge application onto land. Concerted efforts have to be made to standardize sludge application rates on land.

5. SITE SELECTION AND LAND USE CONSIDERATIONS.

Finding a suitable site for land application of sludge is a critical step. The criteria for site selection consider those characteristics which will lead to the renovation of sludge without creating environmental problems outside the site parameter. Based on the factors and criteria described below, an initial screening of sites is done. After the number of potential sites is narrowed, each site should be evaluated in detail, taking into consideration operational techniques and potential environmental impacts.

The main factors that affect the choice of an application site are (42): (i) the location of the facilities and the associated land needs, (ii) the physical environment of the application site, and (iii) population densities and land use.

5.1 Facilities and Associated Land Needs

From the point of view of economics and ease of handling, it is essential to construct treatment plants as near as possible to the land application site or vice versa. But treatment plants are generally located near a stream or river for convenience in discharging the treated effluent and usually downstream from the community in an area that is considered the storage or industrial sector. Similarly, storage facilities are generally located either at the treatment plant or on the application site. Locations near a sparsely populated area are most favourable to avoid complaints about odors and other nuisances. As mentioned before, the method and rate of sludge application will also impose comtraints on site selection. Several physical characteristics of a particular site (e.g. soil type, vegetative cover, topography, etc.) must be evaluated to determine whether the site is acceptable. The availability of buffer zones around the application site to control dispersion of aerosols and to minimize potential problems with nuisance odors, aesthetics, etc. should also be considered in site evaluation.

5.2 Physical Environment of Application Site

Important site characteristics include climate, landscape, parent material, soils and vegetation.

Climate is a major factor in determining the suitability of a site for land application. It strongly affects the overall feasibility as well as the ultimate design of land treatment systems (4). Suitable temperature and moisture conditions are necessary for organic waste decomposition and for growth and development of vegetative cover, key factors in most successful land treatment operations. Low temperatures reduce biological activity and thereby reduce the potential for waste renovation. Prolonged wet periods also impair renovation because saturation affects aeration, and the likelihood of surface runoff is increased. Adverse temperature and moisture conditions necessitate waste storage during the period.

Ideal sites for sludge application should have the following landscape, parent material and soil characteristics although less than ideal sites may sometimes be usable with proper design and management (43).

Important landscape requirements are: (i) A closed or modified closed drainage system (Fig. 12) for containment of the sludge and its by-products until the risk from potential environmental contaminants has been removed by physical, chemical, or biological reactions of the soil, and (ii) Slopes less than 4%; steeper gradients may be acceptable on coarse-textured soils or where management practices or application methods reduce erosion hazards (43). Maximum ground slopes of 5 to 8 percent have been suggested (13).

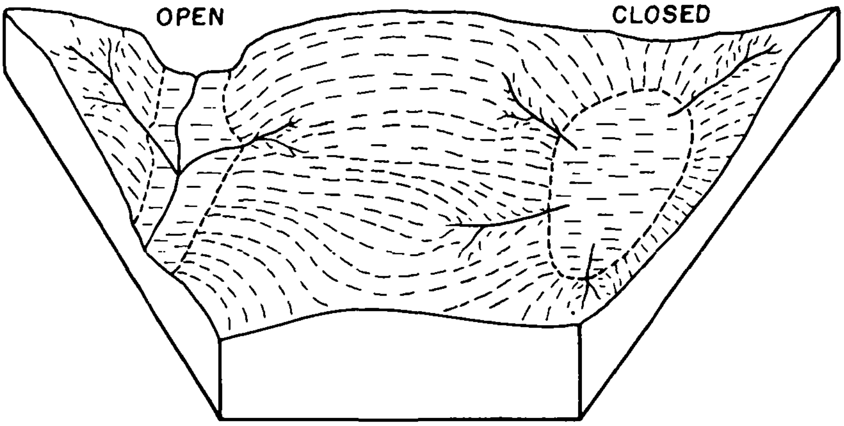


Figure 12. **Diagrammatic Representation of Open and Closed Drainage Systems (43).**

The following characteristics of parent material are important in site selection: (i) Medium-textured materials, finer-textured or high bulk density materials are suitable for sludges if managed properly, (ii) High pH's and/or free carbonates (lime)(43), and (iii) Bedrock and unconsolidated substrata, when present, should be free of coarse conducting layers or conduits to prevent unrenovated wastes contaminants from reaching the groundwater, and should always be at least 4 to 5 feet below the soil surface (4,43).

Soil should have the following characteristics: (i) High surface infiltration capacity and moderate subsoil permeability (1.5 to 15 cm/h or 0.6 to 6.0 in./h) (4,13,43). (ii) A soil thickness of at least 3 to 4 feet (0.91 to 1.22 meters) without restrictive layers (4,43). (iii) Well-drained (water readily removed from the soil either by subsurface flow or percolation) or moderately well-drained (soils seasonally wet e.g., high water table in spring) soil conditions to provide oxidizing conditions throughout most of the year; less well-drained soils if adequately tiled (4,13,43). (iv) Moderate to high moisture supplying capacity (15 to 20 percent by volume) (43) with available water capacity values greater than 6 in./upper 4 ft. (15.2 cm/upper 1.22 meters) (4). (v) Alkaline or neutral soils of pH 6.5 to 8.2 to control heavy metal solubility (13,43). (vi) Medium and high levels of organic matter in the surface horizon (43).

Another important criterion in site selection and system design is vegetation. Vegetation improves water infiltration at the soil surface, provides additional surface area for intercepting water, and reduces the impact of water drops on the soil surface, thereby helping to control erosion. Plants also remove water and large quantities of nutrients from the soil profile. Thus the suitability of the crop in the site for sludge application is an important requisite (42).

5.3 Land Use and Population Densities

Knowledge of current land use in an area indicates how much land is potentially suitable and/or available for waste application. For example, agricultural land can often be used for waste treatment. Abandoned farmland and forest land may also be suitable. A cursory review of land use maps can avoid consideration of areas with urban or industrial development, historical value, or unique environmental features. If the possible site is limited to land already owned by a municipality or industrial concern, the uses of the land surrounding the site should be evaluated to determine if these uses are compatible with a waste application system. Projected land use plans also eliminate certain areas from consideration (4).

In selecting a site for land application of sludge, people's considerations cannot be overlooked and must be examined very carefully. Social acceptance, future population growth (necessitating increased land areas for later expansion) and other public policies are important considerations (42).

It must be emphasized that the principles given above are only guidelines for the selection of a sludge application site. On-site evaluation by qualified scientists and engineers is essential prior to final site selection. Published reports on climate, soils, geology, topography and hydrology may also be consulted to get up-to-date information on the above factors.

6. VEGETATION ASPECTS.

A good cover of vegetation in sludge land application sites improves the ability of the soil to accept and renovate sludges in several ways.

6.1 Roles of Vegetative Cover.

The roles of vegetation in waste treatment are the following (4,13,30,42):

(a) Plant Cover Controls Erosion.

Erosion has an important bearing on land treatment because the waste absorbing abilities of the soil are reduced by erosion. The impact of water dropping on bare ground initiates soil erosion and results in surface runoff. When vegetation and decaying plant residues cover the soil, they cushion the impact and the chances of water detaching and carrying away soil particles is reduced. As shown in Fig. 13, sod crops are most effective among common agricultural plants followed by rotations in which a series of crops are alternately grown, such as corn, wheat, and clover. Small grains, such as wheat and oats, are the next best in preventing soil loss, followed by row crops like corn.

(b) Vegetation Improves Infiltration and Permeability.

Vegetation speeds up the rate at which water enters the soil surface. Infiltration varies with one type of vegetation to another. This depends on the tillage necessary for each crop and the compaction due to the impact of raindrops during the uncropped period. Fig. 14 gives a comparison of infiltration rates under various types of vegetation. Vegetative cover also adds considerable organic matter to the soil, which is the chief agent for increasing the infiltration rate. Infiltration rate has a bearing on emanation of offensive odor caused by pooling of sludge. Soil permeability is also maintained and increased by the extension of root growth.

(c) Plant Cover Removes Water from Soil Profile.

Vegetation absorbs water from the soil profile and this water is lost to the atmosphere from the plant leaves through transpiration. This supplements loss of water from the soil due to evaporation, thus accelerating the drying and aerating of soil between sludge applications.

(d) Vegetation Utilize Nutrients in Sludge.

Nutrients contained in municipal sludges can cause harm when discharged to bodies of water. Nitrogen and phosphorus, in excess, are the major causes of eutrophication in surface water. Vegetative cover on the waste treatment site uses such elements as nutrients for growth. Some nutrient removal rates by crops are shown in Fig. 15. It can be seen that the removal of absolute quantities of nitrogen and phosphorus tends to differ by a factor of about 10. It should also be noted that the form as well as the total amount of plant nutrients affect the uptake by plants. In the case of sludge, where much of the applied nitrogen is in organic form, it will be available for plant uptake only after microbial decomposition.

(e) Crops Provide Economic Returns.

In some instances, financial return from the crop produced may help offset the costs of operating a land application system. Experience with existing systems have shown that the return on crops offsets only a part of the overall operation and maintenance expenses.

(f) Planted Area Improves Aesthetic Appearance.

A planted area is better looking than bare ground or a weed patch. Public acceptance of the presence of a sludge land application system in a community depends to a certain extent on the appearance of the site. Hence vegetative cover, selected with an eye toward aesthetic appeal as well as utility, helps in achieving the all-important goal of public acceptance.

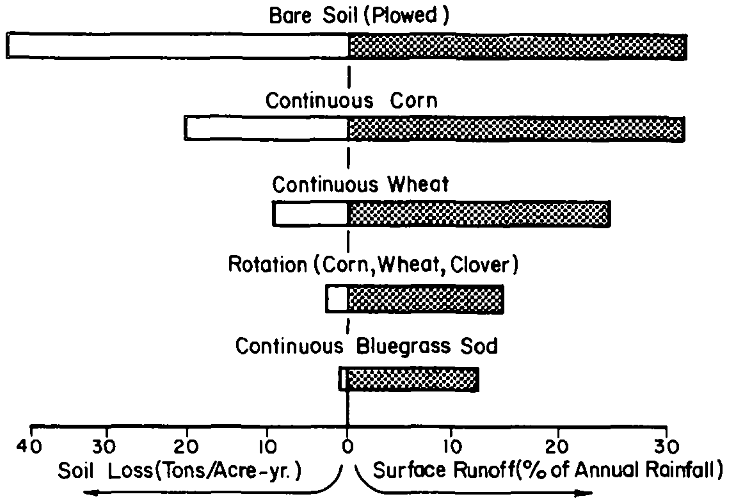


Figure 13. Cropping Systems Differ in Ability to Control Surface Runoff and Erosion. These Data are Average Annual Values Over a 14-year Period on a Silt Loam Soil (3.7% Slope, 90-Feet Long). Average Annual Rainfall was Approximately 40 Inches (4).

1 ton/acre = 2.24 Mg/ha
1 in = 2.54 cm

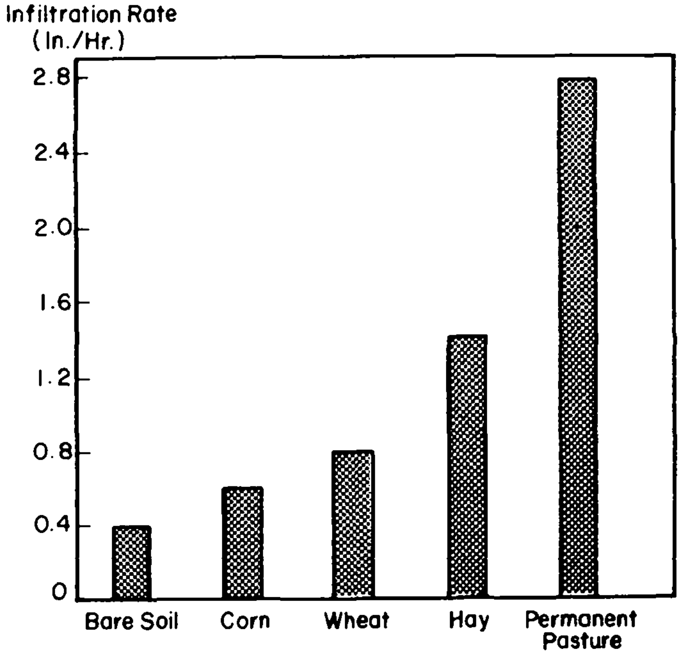


Figure 14. The Type of Soil Cover Markedly Affects Water Infiltration Rates (Cited in 4).

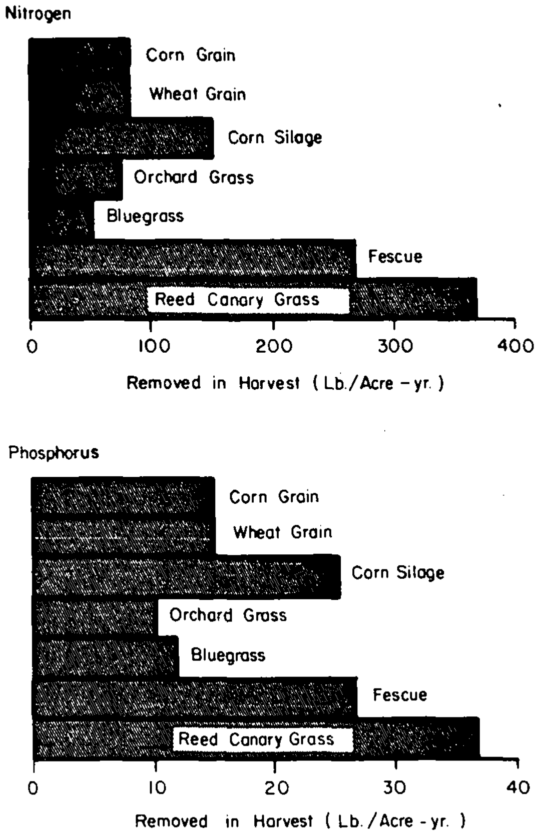


Figure 15. The Relative Amounts of Nitrogen and Phosphorus Removed in Crop Harvest Vary With the Type of Crop and the Proportion of the Tissue Removed. Note that Nitrogen and Phosphorus Scales Differ by a Factor of 10. (Cited in 4).
1 lb/ac.yr = 1.12 kg/ha. yr

6.2 Crop Selection

Before intelligent crop selection can be made, analysis of the waste to be applied and of the soils involved must be made. Analysis of the crops grown may also be necessary to protect the food chain or monitor site longevity if an unusually high level of any nutrient or potentially toxic element is applied. The sludge should be analysed for electrical conductivity, sodium adsorption ratio (SAR), HCO_3, B, and Cl when it is to be used for irrigation. These have all been associated with reduced yields when applied is excess.

According to SOPPER (29), some of the criteria to be considered in the selection of vegetative cover to be utilized on a land application site include (29): (i) Water requirements and tolerance, (ii) Nutrient requirements and tolerance, (iii) Optimum soil conditions for growth, (iv) Season of growth and dormancy requirements, (v) Sensitivity to toxic heavy metals and salts, (vi)

Nutrient utilization and renovation efficiency, (vii) Ecosystem stability, (viii) Length of harvesting rotation, (ix) Insect and disease problems, (x) Natural range, and (xi) Demand or market for the product.

If there is no limitation in the selection of plant species, it is advantageous to maintain or utilize the normal cropping patterns found in the community (44,45). These patterns have evolved because of favorable soil, climatic, and economic conditions and will probably maintain certain advantages in the sludge application system as well. One possible exception could occur if the cropping pattern were restricted to a single crop. In this case, additional crops could increase the opportunity of applying sludge during a variety of seasons.

Row crops such as corn and soybeans probably offer the least sludge application flexibility, but can be used on sludge amended soils with few constraints. Corn has an added advantage in that it accumulates little cadmium. In terms of nutrient utilization during the growing season, forage crops can be superior to others (45) as depicted in Table 22. Removal of these grasses from the site maximizes nutrient reuse. However, a continuous sod makes sludge applications more difficult. Although small grain crops use lower amounts of nutrients as compared to row crops or forages, and are subject to lodging (45), in general terms, grain crops present a lesser heavy-metal hazard to the food supply than do forages, pastures and leafy vegetables (46). Vegetables, especially leafy and root vegetables are not recommended on sludge amended soils because they are heavy metal accumulators (45). Specific considerations for some selected crops are given in Table 23 which may be useful in the selection of cover vegetation for sludge land application.

Forest lands may also be used for sludge application. Trees take up as much nutrients as some agriculture crops do during a single growing season, but much of the uptake is redeposited, as only the stemwood is removed every 40 to 100 years. Thus forest land have not been considered the best site for taking up nutrients after application of waste. However if the entire above ground crop of trees is chipped and removed at shorter intervals such as every 5-20 years, more nutrients are taken up from the soil. Undisturbed forest land, however is the best vegetative cover for promoting infiltration (4).

6.3 Agronomic Aspects of Sludge Application

Recently extensive research has been done to assess the effect of land application of sludge on cover vegetation i.e. on their growth, yield, and uptake of nutrients and heavy metals. In this section an attempt will be made to report some of the findings on the effect of sludge application on the growth, yield and uptake of nutrients by vegetation.

A study conducted at the Rosemount Agricultural Experiment Station, Minnesota, attempted to determine the impact of liquid digested sludge applications for three years on crop yields of corn and reed canary grass grown on silt loam soil (47). Total sludge applications through three growing seasons were 17 cm on the corn areas and 13 cm on the grass areas which were equivalent to 28 and 20 tonnes/ha total solids and 1610 and 1260 kg/ha total N, respectively. Corn yield means for three seasons were 14.5 tonnes/ha fodder and 6.8 tonnes/ha grain (108 bu/ac) on the sludge treated land as compared to 13.8 tonnes/ha fodder and 6.4 tonnes/ha grain (102 bu/ac) on the fertilized control area. Reed canarygrass dry matter yields for one cropping season were 9.7 tonnes/ha on the sludge-treated areas as compared to 7.8 tonnes/ha on the fertilized control area. Plant tissue showed normal concentrations of N, P and K (47). Lysimeter studies at Illinois (48) with digested sewage sludge have also

Table 22. Removal of Different Elements from Soils by Crops (Cited in 45).

Crop	Yield per acre	Removal (lbs/acre)							Conc. (mg/kg)			
		N	P	K	Ca	Mg	S	Na	Fe	Mn	Cu	Zn
Corn grain	100 bu	80	15	17	2	8	7	1	66	14	6	43
Grain sorghum	80 bu	80	14	15	2	8	7	2	90	30	20	28
Soybeans	32 bu	105	11	29	5	5	4	4	70	26	14	–
Peanuts	2,500 lb	94	8	12	2	4	6	14	16	–	–	–
Cottonseed	1,800 lb	62	13	20	3	6	4	5	114	10	41	–
Wheat	60 bu	81	15	18	2	4	6	3	73	80	11	23
Rice	6,000 lbs	78	14	9	3	4	3	3	96	48	9	5
Barley	75 bu	67	15	20	3	5	6	1	87	26	12	25
Sugarbeets	25 t	21	20	125	20	15	1	40	227	765	30	–
Corn silage	20 t	136	24	118	34	24	12	3	929	228	47	98
Alfalfa hay	7 t	332	31	212	197	38	43	19	1,306	282	74	92
Coastal bermuda hay	9.5 t	243	29	270	74	27	–	–	–	–	–	–
Reed canarygrass hay	7 t	169	30	282	41	31	–	47	816	503	65	–
Potatoes	30 t	210	30	288	6	18	12	12	544	240	102	–
Tomatoes	20 t	71	11	98	5	6	–	1	92	–	–	–
Lettuce	12.5 t	34	5	42	5	3	–	2	55	–	–	–
Carrots	20 t	58	12	112	12	8	8	15	104	68	24	–
Snap beans	5 t	27	4	21	5	3	–	1	32	–	–	–
Dry beans	1,800 lbs	64	8	22	3	3	4	1	64	15	8	–
Loblolly pine	annual growth	9	1	4	5	2	1	–	–	–	–	–

1 lb/ac = 1.12 kg/ha
1 kg = 2.2 lb
1 bu = 35.2 ℓ
1 t = 0.90718 tonnes

Table 23. Selected Crops and Considerations for Municipal Waste Application (Cited in 42).

Crops	Advantages	Disadvantages
Corn (for grain)*	High value, extensive acreage, good response to irrigation, high nutrient uptake	Short period for application, low infiltration rate, nitrate accumulation in silage crop, annual crop
Soybeans	Extensive acreage, high nutrient uptake, high value, used in double cropping rotations	Less adaptable, more sensitive to application on leaves, annual crop
Small grain	Extensive acreage, tolerant of salts, minimize erosion	Low nutrient uptake, annual crop, lodging and crop diseases, short period for application
Grass crops (forages)	Perennial plants, fibrous root system, sod forming — minimize erosion, long growth period, high infiltration rate, high uptake of nutrients, tolerant of salts, tolerant of a wide range of ecological conditions	Marketing product may be difficult, nitrate accumulation can injure grazing animals, limited application timing to off-grazing periods

*Corn for silage would have similar advantages plus removal of large quantities of nutrients.

indicated increased yield with no apparent deleterious plant nitrogen composition in the case of crops like soybeans, grain sorghum, reed canarygrass, and corn.

Studies were conducted in Wisconsin (49) to determine the effect of liquid digested sewage sludge applied at rates based on typical fertilizer N applications to high sludge disposal loading rates on crop yields, the residual fertility of the sludge, and the amounts of sludge-applied N and P recovered by the crops. The rates used were 0, 3.75, 7.5, 15, 30 and 60 tonnes dry solids/ha on a sandy loam and a silt loam. In one experimental area, rye was grown as the first crop followed by corn for 3 years to test the residual crop responses. Another area was initially cropped to sorghum-sudan followed by 1 year of corn. Yields of the first crop following sludge application typically increased significantly upto the 7.5 tonnes/ha rate on the silt loam soil and upto the 15 tonnes/ha on the sandy loam soil. This corresponded to an application of 190 and 380 kg/ha of available N, and 183 and 366 kg/ha of total P for the 7.5 and 15 tonnes/ha rates, respectively. In some cases, the 30- and 60 tonnes/ha depressed the first crop yields, possibly because of large amounts of soluble salts in the sludge. Residual benefits from sludge were evident for at least 3 years at the higher treatment rates. Increasing rates of sludge generally resulted in marked increases in the concentration of N and P in plant tissue. Total recovery by upto 4 successive crops averaged about 50% for available N and 7% for P at the low treatment rate, and about 14% N and 3% for P at the highest treatment rate. An experiment conducted at Ithaca, New York (204), in which beans, carrots, peas, and potatoes were grown on soil amended with domestic sewage sludge at 224 dry tonnes per hectare, showed increased concentrations of ascorbic acid and riboflavin when compared to the control. There was also a notable difference in vegetable flavour.

At Colorado, sludge was added to a loamy sand at rates of 0, 25, 50, 100 and 125 tonnes/ha (dry weight basis) in the field (50). Severe inhibition of sorghum-sudangrass and millet resulted when seeded shortly after the sludge was incorporated into the soil. Standcounts for wheat seeded about 3 months after sludge incorporation showed no germination inhibition. This was attributed to the dissipation of the inhibitory factor or the increased tolerance of wheat as compared to the other plants. A decrease in sorghum-sudangrass yields was noted with sludge addition. This was apparently a result of poor germination rather than growth inhibition due to sewage sludge. In general yields on sludge-treated plots were greater or equal to no-sludge plots. Based on wheat yields, the optimum sludge application rate in this study was between 25 and 50 tonnes/ha. In no case, even at 125 tonnes/ha was the elemental content of the wheat grain outside normal ranges expected in plant tissues.

Greenhouse studies using composted sludge at Beltsville, Md, on tall fescue at four rates (0 to 134.4 tonnes/ha, dry weight) and on two soils (loamy sand and silt loam) have indicated linear yield relation to compost amendment for both soils (51). It was found that the mineralization of compost organic N was the limiting factor in grass yield. Another study to investigate the residual effect of liquid digested sludge on a coastal bermudagrass grown on sandy clay loam amended with 6.9, 13.8, 20.0 and 40.0 cm sludge showed no detrimental effect on the yield from sludge application, thus establishing the suitability of coastal bermudagrass for a sludge disposal area (52).

A four year field study was conducted at Minnesota in which anaerobically digested sludge was applied to sandy soil cultivated with edible snap bean. A total of 0, 350, 700 and 1,400 tonnes/ha was applied in 3 equal applications in the first phase and a single application of 0, 112, 225 and 450 tonnes/ha was applied in the second phase of the study. Crop yields increased as rates of sludge application increased under both cultural systems and often exceeded those of a well-managed, fertilized control (53).

Municipal anaerobically digested sludge and wood waste mixtures have been used to enhance crop yield (54,98). At Colorado, various combinations of sewage sludge and wood wastes at 4 rates ranging from the equivalent of 22.4 to 224 tonnes/ha were used in a greenhouse study with wheat as the test crop. Every mixture except 50% bark - 50% sludge caused an increase in wheat growth compared to the control. Greatest wheat growth occurred for the 224 tonnes/ha of 50% wood - 50% sludge, 25% bark - 75% sludge, and 25% wood and bark - 75% sludge treatment. In another greenhouse study (55), 2 rates of dried anaerobically digested sewage sludge were applied to tall fescue and alfalfa grown during a 2-year growth period, on an agricultural soil and on acid strip-mine spoil. Sludge applications of 314 and 627 tonnes/ha significantly increased yields of plants grown on agricultural soil. On strip-mine spoil, yields of tall fescue and alfalfa were significantly increased at the application rate of 627 tonnes/ha, probably due to the higher soil pH (6.0) attained. In all treatments, the yields of alfalfa were greater than that of tall fescue, although the areal coverage of fescue exceeded that of alfalfa. Studies with rye (56) grown under controlled conditions on a sandy loam amended with digested secondary sludge at different rates (0 to 10%, dry weight basis) indicated that plant yields from successive clippings (3 clippings) decreased as sludge application rates increased.

There have been numerous reports (16,57-67,214) of research in land application of sludges from Canada. Field studies with anaerobically digested sewage sludges, resulting from treatment of sewage with $Ca(OH)_2$, $Al_2(SO_4)_3$, or $FeCl_3$ for phosphorus removal, were conducted near Guelph, Ontario, using corn and bromegrass as the experimental crops (66). The rates of application supplied 200, 400, 800 and 1,600 kg N/ha each year for 3 years. Bromegrass yields were increased by sludge application supplying upto 800 kg N/ha and there was an appreciable residual effect of sludge nitrogen on the grass yield. On loam and clay loam soils, there was no further increase in the yield of corn with rates of sludge in excess of 200 kg N/ha and there was little or no difference in corn yield between the sludge used on the loam soil. On the clay loam, the Ca-sludge appeared to benefit the corn most. There was no yield response to sludge on the loamy sand. However, nitrate concentration in corn stover was increased by high rates of sludge. Phosphorus and magnesium concentrations in corn grain and stover were unaffected by treatment (67). Phosphorus concentration in bromegrass was increased by Ca-sludge and, to a lesser extent, by Fe-sludge additions. The Ca-sludge treatments resulted in a lower K concentration in corn stover and seedlings than either Al- or Fe-sludge treatments. Increasing sludge application reduced K concentration in bromegrass. Sludge application had no effect on Ca concentration in corn grain or stover in loam and loamy sand, but increased it in corn seedlings and stover in clay loam. Calcium in bromegrass was increased by sludge treatment, with the Ca-sludge having the greatest effect. Magnesium in bromegrass also increased by sludge applications (67).

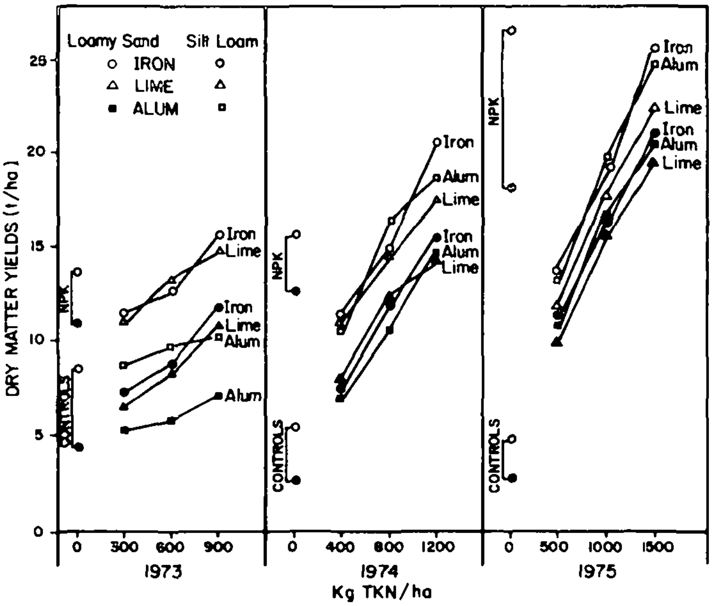


Figure 16. Orchard Grass Yields vs. Sludge Application Rates 1973-75 (16).

A long term lysimeter study was initiated in 1972 in Canada (16), using liquid digested alum, iron or lime sludges and orchard grass grown on loamy sand and silt loam. Increasing sludge application rates significantly increased yield on both soils for all sludge types (Fig. 16).

Forest trees have also been the subject of intense research to test the feasibility and suitability of applying sewage sludge to such wooded areas. Growth-response studies have been conducted, a few of which will be mentioned here to exemplify the effects.

A 10-year-old white spruce plantation established on sandy soil gave a 30-percent height-growth response over control trees 4 years after application of 500 pounds per acre (561.4 kg/ha) of sewage sludge (68) near Quebec, Canada (Fig. 17). SOPPER (29) reported a study conducted in Scranton, Pennsylvania, where heat-dried sludge applied to a burned anthracite refuse bank nearly doubled the height growth of the hybrid poplar at 150 tonnes/ha at the end of five growing seasons (29). After 5 years the production of biomass more than quadrupled with the addition of sludge (Table 24). Reports from Durham, New Hampshire (69), of dewatered and limed sludge application at 25 and 125 wet tonnes/ha on sandy loam soils in a hardwood stand have shown that there was no significant differences in basal-area growth among control and treated plots for the first two growing seasons.

From the discussion in this section, it can be seen that, although work is in progress, the agronomic influences of sewage sludge application to land have yet to be clearly defined, and efforts have to be made to establish definitive sludge-plant relationships and sludge application limitations.

7. SOIL ASPECTS.

7.1 Soil Treatment Mechanisms

The use of the soil as a treatment medium may be a new concept to some since historical usage has stressed land application for waste "disposal". Nothing, however, is actually disposed of. Instead some materials pass through the soil and into the groundwater, some are utilized by growing plants, while others are retained almost indefinitely within the soil. Proper design of land application facilities must relate the fate of pollutants to the properties of soil with which they may interact and minimize the fraction of contaminants passing through to groundwater. There are several separate unit processes that can be adopted for removal of SS, TDS, BOD_5, N, P, or potentially toxic elements and an almost unlimited combination of these which ultimately comprise the treatment system (4).

Waste treatment mechanisms that occur in soils can conveniently be categorized as physical, chemical, and biological. Within each category, various processes act to remove or alter specific waste constituents and these have been described in detail by LOEHR, et al. (4).

TREATMENT MECHANISMS

PHYSICAL	CHEMICAL	BIOLOGICAL
Filtration Dilution	Adsorption Precipitation	Organic Matter Decompostion Inorganic Transformations Assimilation

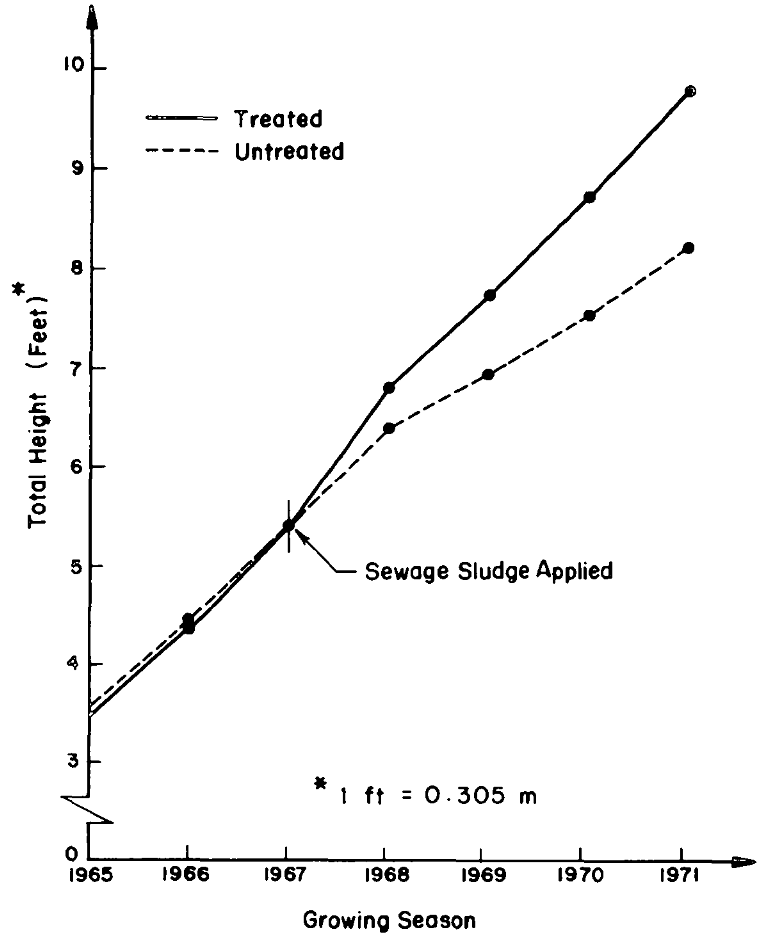


Figure 17. Average Total Height of White Spruce on Treated and Untreated Sites (68).

Table 24. Average Height and Diameter Growth of Hybrid Poplar at the End of the Fifth Growing Season (29).

Sludge treatment	Height	Diameter
metric tons/ha	m	cm
0	2.46	2.5
40	3.41	4.2
75	3.80	4.7
150	4.53	6.1

7.2 Soil Limitations For Application of Sewage Sludge

The nature of the soils on which the sludge is applied influences the feasibility of sludge utilization. Sludge can be applied to land beneficially only when soil properties are known and properly considered. If the system is designed to compensate for less-than-ideal properties, soils with a wide range in physical, chemical, and biological characteristics can be used successfully. Although very few soils are totally unsuitable for land application of sludge, some, however, are better than others. In the United States, for example, the Soil Conservation Service (SCS) and several states have developed tables which rate the suitability of soils for receiving sewage sludge and these are shown in Tables 25 and 26. In addition to consulting such tables, as mentioned earlier, onsite investigations should be conducted for specific site selection and for system design.

Sludge applied to land undergoes transformation and is decomposed to form simpler elements. The physical, chemical and biological characterstics of the soil influences changes. In turn, the sludge also affects some of the physical, chemical and biological properties of the soil. Research is in progress to assess these changes in the soil, some of which are mentioned below.

7.3 Changes in Soil Physical Conditions

The addition of sludges and sludge composts to soils is known to improve the soils physical condition (15,72) by: (i) increasing the water holding capacity, (ii) enhancing aggregation, (iii) increasing soil aeration, (iv) improving permeability, (v) increasing water infiltration, and (vi) decreasing surface crusting.

Several studies have reported changes in soil physical conditions. For example HINESLY, et al. (48) found that water infiltration rates were unaffected by a dry sludge crust on the soil surface (48). A sludge crust of upto 3.8 cm has been reported by TOUCHTON, et al.(52) for a total sludge application rate of 40.0 cm (52). KELLING, et al. (73) reported slight increases in infiltration rate resulting from sludge incorporation. EPSTEIN (74) reported an increase in percent stable aggregates and no change in "available water" in a laboratory incubation experiment utilizing high sludge application rates. Sludge compost application at high rates in a field experiment caused a shift in the soil water retention curve and increased the "available water" of a Maryland silt loam (75). KLADIVKO and NELSON (76) have shown in a one year field study that application of sludge at 56 tonnes/ha generally improved the physical condition of three Indiana soils. Significant increases were observed in the size of water-stable aggregates, large pore space, 1/3-bar and 15-bar water contents and a significant decrease in bulk density. Sludge promoted no significant change in water infiltration rates or water-holding capacity during the one year study (76).

7.4 Changes in Soil Biological Conditions

The effect of sewage sludge application on soil flora and fauna has not received much attention except for a few recent studies. In one such study by McILVEEN and COLE (77), findings suggest that sludge may be similar to manure in the effect it has on soil microflora. Corn was used as the experimental crop and it was found that the algal coverage of the soil surface increased at application rates of 22 and 44 tonnes/ha, as also the bacterial and actinomycete population. In another study on the effect of sludge on earthworm populations in the soil, sewage sludge organic matter was found to increase the number and

Table 25. Limitations of Soils for Application of Biodegradable Solids and Liquids (U.S., interim) (71).

Item affecting use	Soil-limitation rating		
	Slight	Moderate	Severe
Permeability of the most restricting layer above 60 in.[a]	0.6-6.0 in./hr	6-20 and 0.2-0.6 in./hr	>20 and <0.2 in/hr
Soil drainage class	Well drained and moderately well drained	Somewhat excessively drained and somewhat poorly drained	Excessively drained, poorly drained, and very poorly drained
Runoff	Ponded, very slow, and slow	Medium	Rapid and very rapid
Flooding	None	None for solids; only during nongrowing season allowable for liquids	Flooded during growing season (liquids) or anytime (solids)
Available water capacity from 0-60 in. or to a root-limiting layer	>8 in. (humid regions) >3 in. (arid regions)	3-8 in. (humid regions) Moderate class not used in arid regions	<3 in. (humid regions) <3 in. (arid regions)

[a] Moderate and severe limitations do not apply for soils with permeability <0.6 in./hr:
(1) for solid wastes unless the waste is plowed or injected into the layers having this permeability or evapotranspiration is less than water added by precipitation and irrigation, and
(2) for liquid wastes if layers having that permeability are below the rooting depth and evapotranspiration exceeds water added by precipitation and irrigation.

1 in. = 2.54 cm.

Table 26. Soil Limitations for Sewage Sludge to Agricultural Land at Nitrogen Fertilizer Rates in Wisconsin (Cited in 45).

Soils features affecting use	Degree of soil limitation		
	Slight	Moderate	Severe
Slope[a]	Less than 6 percent	6 to 12 percent	More than 12 percent
Depth to seasonal water table	More than 4 ft	2 to 4 ft	Less than 2 ft
Flooding and ponding	None	None	Occasional to frequent
Depth to bedrock	More than 4 ft	2 to 4 ft	Less than 2 ft
Permeability of most restricting layer above 3 ft	0.6 to 2.0 in./hr	2.0 to 6.0 in./hr 0.2 to 0.6 in./hr	Less than 0.2 in./hr More than 6 in./hr
Available water capacity	More than 6 in.	3 to 6 in.	Less than 3 in.

[a] Slope is an important factor in determining the runoff that is likely to occur. Most soils on 0 to 6 percent slopes will have very slow or slow runoff soils on 6 to 12 percent slopes generally have medium runoff, and soils on steeper slopes generally have rapid to very rapid runoff.

1 ft = 0.305 m
1 in = 2.54 cm

biomass of the species Allolobophora longa and Lumbricus terrestris, whereas other species were suppressed, resulting in a heavy dominance of these two species compared with the effect of farmyard manure, where the number of the individual species is more balanced (78). NEWHAUSER, et al. (225) tested the suitability of 'simple' nutrients (such as protein or pure carbohydrates), microorganisms and organic wastes, manures, sludges and paper as food for the earthworm E. foetida. It was found that nutritional benefits are derived only from cellular mass. Thus E. foetida should be considered seriously for use in natural ecosystems and commercial enterprises for accelerating the decomposition of biodegradable wastes, included sludge.

More is to be learnt about biological implications of sludge land application, since these play an important role in sludge decomposition and transformation in the soil in addition to posing hazards to plant and animal life. The effect of sludge application on pathogen survival is described in the section on "Potential Problems Associated with Land Application of Sludge" later.

7.5 Changes in Soil Chemical Conditions and Sludge Decomposition

Addition of sludge to soils may cause changes in soil pH, cation exchange capacity, salinity and the levels of various elements in the soil (30). The chemical properties of the soil are important for assessing: (i) potential treatment efficiency, (ii) need for soil amendments, and (iii) baseline levels of any constituents expected to accumulate in the profile and cause long term problems. Soil pH affects both chemical and biological treatment mechanisms.

SOON, et al. (67) found that Ca-sludge increased the soil pH and Fe-sludge reduced the pH slightly at rates supplying up to 1600 kg N/ha each year. HINESLY, et al. (79) have reported that there was no change in the pH of the soil from application of liquid sludge for 3 years. Similarly, the CEC of the soil has been reported to have increased in proportion to the organic-carbon residue in the soil after sludge application (79). EPSTEIN, et al. (75) reported a threefold increase in soil CEC as a result of addition of sludge and sludge compost in Beltsville, Maryland. They also reported increases in salinity and chloride levels of the soil to a level which may affect salt-sensitive plants. Increase in soil CEC as a result of sludge application has also been reported by KLADIVKO and NELSON (76). The levels of various elements in the soil is a function of sludge decomposition. Sludge decomposition, in turn, is governed by many factors. For example, subsurface application of sludge impedes biological degradation of organics some what, due to the lower temperature and oxygen concentrations of sub-surface soil (17). A review of the nitrogen and phosphorus transformations in the soil enables a better understanding of the sludge decomposition mechanism in soils.

LOEHR, et al. (17) have vividly reviewed the nitrogen and phosphorus behaviour in terrestrial systems. The various forms of nitrogen are interconnected through a series of complex transformations, which collectively constitute the nitrogen cycle (Fig. 18).

Nitrogen enters terrestrial systems in sludge applications, natural precipitation and through fixation of molecular nitrogen from the atmosphere by specialized microorganisms. Sludges contain nitrogen in the forms of organic-N, ammonium-N, and nitrate-N. Since the annual nitrogen removal by crops seldom exceeds 300 lb/acre (336.8 kg/ha) and the addition of a small amount of sludge (1 acre-inch) may exceed 300 lb/acre (336.8 kg/ha) of nitrogen, strict nitrogen control will require management methods other than or in addition to crop uptake. Most native nitrogen in soils is bound in organic forms and it is

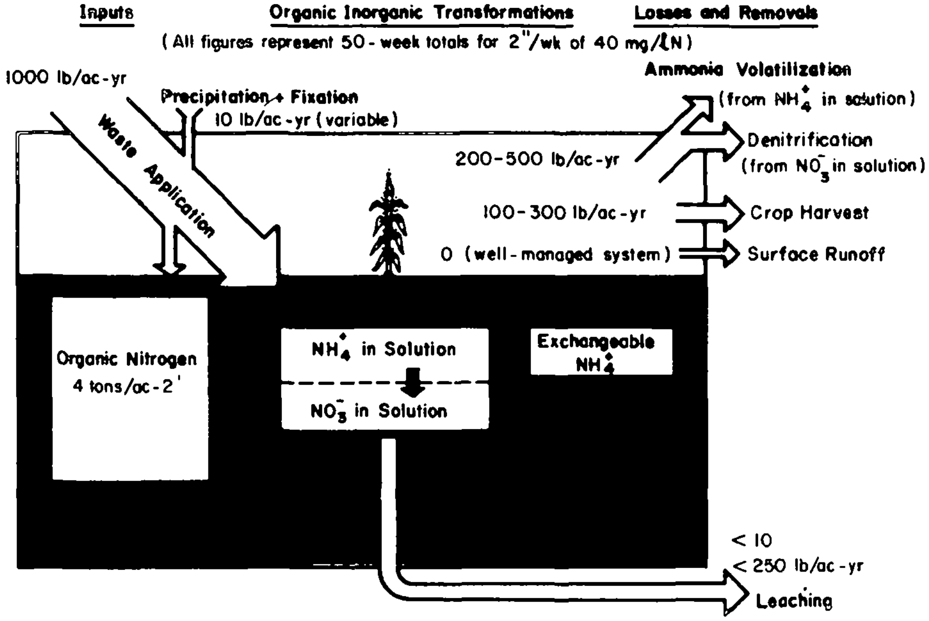


Figure 18. Nitrogenous Materials are Subject to a Series of Complex Transformations in the soil. These Transformations, Mediated by Microorganisms, Environmental Factors, and Management Practices, Determine the Ultimate Fate of Nitrogen Inputs in Terrestrial Systems (17).

1 lb/ac.yr = 1.12 kg/ha.yr

1 acre = 0.405 ha

1 ft = 0.305 m

unavailable to plants and will not leach to groundwater. In the soil, microorganisms slowly transform organic-N to inorganic forms, a process termed mineralization. Mineralization consists of ammonification and nitrification. Ammonification is the conversion of organic nitrogen to ammonia as shown below.

$$\underset{\text{(organic nitrogen)}}{R\text{-}NH_2 + H_2O} \xrightarrow[\text{enzymes}]{\text{microbial}} \underset{\text{(ammonia)}}{R\text{-}OH + NH_3} + \text{energy}$$

At the pH range of most soils (i.e., 4.5 - 7.5), ammonia exists as the ammonium ion (NH_4^+) and only about 5% of the CEC of the soil is available for ammonium adsorption. Ammonium, however, undergoes a further transformation: nitrification, as shown below.

$$\text{Step 1: } 2NH_4^+ + 3O_2 \xrightarrow{\textit{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+ + \text{energy}$$

$$\text{Step 2: } 2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacter}} 2NO_3^- + \text{energy}$$

Nitrification is favoured in well aerated soils, 80-90 degrees Fahrenheit (26.7 - 32.2 degrees Centigrade) temperatures and a neutral to slightly alkaline pH. The major significance of nitrification in sludge application systems is the production of the readily leachable nitrate which is also required for denitrification.

Nitrogen also undergoes immobilization in which inorganic nitrogen is converted into organic nitrogen as a component of microbial tissue. In sludge, which has a low C:N ratio (N content greater than 1.5 by dry weight), mineralization predominates. Nitrogen removal mechanisms from terrestrial systems include ammonia volatilization, denitrification, crop harvest, surface runoff and leaching. In moist, alkaline soils, ammonium salts undergo a chemical reaction resulting in the evolution of ammonia gas (NH_3). 60% of ammonium nitrogen may be lost in the form of ammonia gas in liquid sludge surface application. Incorporation of sludge into soil reduces this loss. Under anaerobic condition, bacteria use the chemically combined oxygen in nitrate to form nitrous oxide (N_2O) and molecular nitrogen (N_2) and this is termed denitrification.

$$\underset{\text{nitrate}}{NO_3^-} \longrightarrow \underset{\text{nitrite}}{NO_2^-} \longrightarrow \underset{\text{nitrous oxide}}{N_2O} \longrightarrow \underset{\text{molecular nitrogen}}{N_2}$$

The bacteria involved in these reactions require organic carbon as an energy source. Thus, to encourage biodenitrification (which has more significance in land treatment systems than chemodenitrification), land application systems must be managed so as to bring nitrate and organic carbon together under anaerobic conditions; this is no simple task. The extent of denitrification is difficult to predict because, by the time nitrogen is converted to a form that can be denitrified, much of the required organic carbon has been consumed. Nitrogen uptake by harvestable crops consitute a significant mechanism for N removal as already explained in Section 6, "Vegetation Aspects".

The magnitude of nitrogen loss in surface runoff is highly variable from one site to another depending on natural precipitation, topography, season, and application rates and methods. If nitrogen inputs exceed the capacity for crop uptake and/or denitrification, leaching of nitrate must be expected.

Fig. 19 depicts a general scheme for phosphorus interactions in a land application system. Although waste inputs of phosphorus occur in both organic and inorganic forms, organic forms predominate in sludges (17). Various forms occur in the soil including phosphorus bound in organic matter (largely humus), dissolved phosphorus in the soil solution, and phosphorus bound in inorganic forms. The freshly added and native organic forms are slowly mineralized by soil microorganisms through normal decomposition processes (1) (numbers refer to Fig. 19). Some of these mineralized P may be reabsorbed and thus temporarily immobilized by the microbes (2). Immobilization is most significant immediately following waste application when the microbial population is rapidly increasing. Dissolved P comprises only a small fraction of the total soil phosphorus. Nevertheless it is from this fraction in the soil solution that plants obtain needed phosphorus for growth and development (3), and from which any leaching loss occurs. Dissolved P is in equilibrium with the much larger amount of phosphorus bound in inorganic forms (4), primarily iron-, aluminium-, and calcium-phosphates. The equilibrium relationship between these forms and

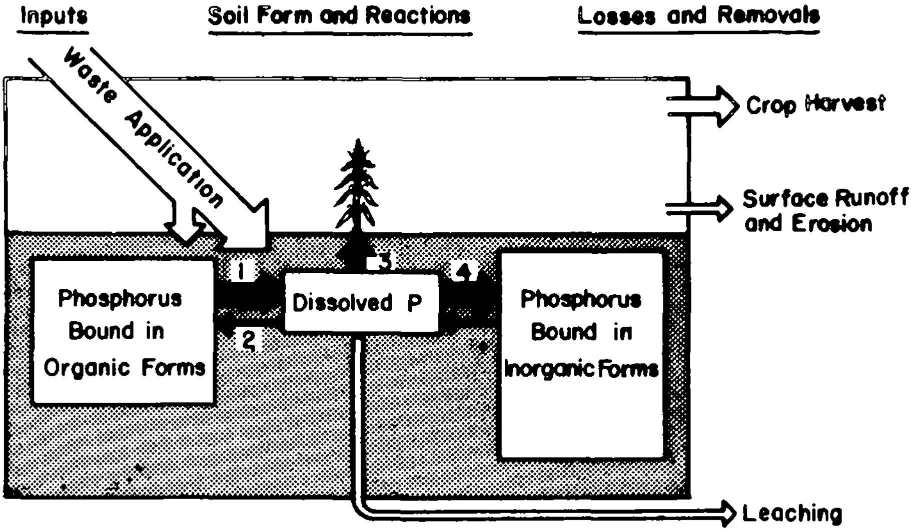


Figure 19. Phosphorus Additions to Soil are Largely Held Either in Organic Combination or by Reaction with Soil Minerals. Dissolved Phosphorus, in Equilibrium with Bound Form, Supplies Plant Needs and is Subject to Leaching (17).

dissolved P is of considerable importance in the overall performance of a land treatment system. It is also to be noted that the pH of the soil determines the form of phosphorus in solution and the way it will be retained, as depicted in Fig. 20. The principle pathways for loss or removal of phosphorus are surface runoff and erosion, crop harvest and leaching. It may also be mentioned that leaching losses of phosphorus are very small in natural systems due to the high fixing power of many soils.

Recently, there has been widespread interest in sludge transformations in the soil and the ultimate fate of the constituents of sludge applied to land. SABEY, et al. (54) reported that the total N, NH_4-N, and NO_3-N residue in the sludge-woodwaste amended soil after harvest of wheat increased as application rates increased. They also reported that caution should be exercised with land applications of 112 and 224 tonnes/ha of 100% sludge and 25% wood - 75% sludge, as well as with 224 tonnes/ha of 25% wood and bark - 75% sludge treatments. Ammonium N did not accumulate excessively (54). Carbon dioxide production from wood, bark and wood-bark mixtures with sewage sludge have also been studied (81). Generally, as the application rate of organic material increased, the carbon dioxide production increased. Attempts were also made to correlate carbon dioxide production with N mineralized and it has been found that microbial respiration is a good index of plant available N in soil, except where plant nutrients are deficient due to microbial immobilization or where toxic factors are limiting to microbial activity.

SABEY (82) has pointed out that most anaerobically digested sludges have considerable ammonium nitrogen (20-60% of total nitrogen) and this is immediately available for plant growth unless the sludge is surface applied, wherein significant amounts may be lost through volatilization. According to him, estimates of the amount of organic nitrogen that becomes available in one season have ranged from 2 or 3% to greater than 50% (82). HINESLY, et al. (48)

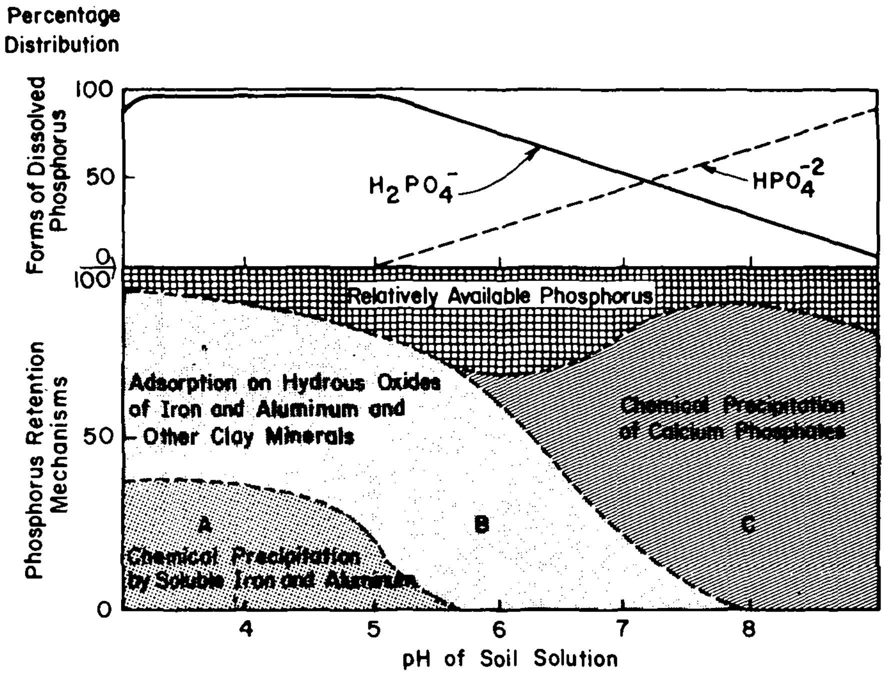


Figure20. Forms of Dissolved Phosphorus Retention Mechanisms Vary with pH. In the Acid Range, Phosphates are Bound with Iron and Aluminum Compounds (A,B) while in the Alkaline Range, Calcium Phosphates Predominate (C). Maximum Availability of Phosphorus for Plant Uptake as well as Leaching Occurs between pH 6 and 7 (17,80).

reported a laboratory investigation of ammonia volatilization from liquid digested sludge in which the results indicated that, at a temperature of 25 degrees Centigrade and pH of approximately 7.5, the rate of deamination of organic nitrogen in the sludge exceeds the rate of ammonia movement to the surface and transfer to atmosphere. Loss of gaseous ammonia at the surface of the sludge was nearly linear with time. They also reported a mathematical model of ammonia volatilization which permits prediction of the influence of variables such as depth, pH, and mixing on nitrogen loss (48). A similar model to describe volatile loss of ammonia by convective mass transfer has been developed by ENGLISH, et al. (83), which can be used to predict volatile losses of ammonia from sludge applied to land (83). WILSON (84) studied nitrification in dried sewage sludge from either predominantly domestic or industrial sources. He found that reduced nitrification at high rates (4 and 16 mg/g) of industrial sludge was caused by metals like Zn, Cd and Pb, whereas at the highest rate (16 mg/g) the domestic sludge reduced nitrification only slightly (84).

BEUCHAMP, et al. (85) conducted experiments to investigate nitrate production in soils treated with Ca-, Al-, and Fe-sludge. They found that chemical treatment of the sludge with $Ca(OH)_2$, $Al_2(SO_4)_3$, and $FeCl_3$ was not responsible for the difference in the nitrate production. In general 17 to 30%

of the sludge N was nitrified in 16 weeks under laboratory conditions (85). In another experiment conducted by SOON, et al. (66) with the same kind of chemically treated, anaerobically digested sewage sludges, high nitrogen concentrations of nitrate (NO_3^-) were found up to 75 and 90 cm soil depth at application rates supplying 400 and 800 kg N/ha, respectively (66). BEUCHAMP, et al. (86) measured ammonia volatilization from newly applied anaerobically digested sewage sludge in the field, using an aerodynamic method. It was estimated that during a 5-day experimental period, 60% of the 150 kg ammoniacal N/ha applied in sludge was volatilized and during a 7-day experimental period, 56% of the 89 kg ammoniacal N/ha applied was volatilized. However, sampling the sludge layer and soil beneath it, indicated considerable variability in volatilization estimates (86). An experiment conducted in Beltsville, Maryland, by EPSTEIN, et al. (87) indicated that sewage sludge and sludge compost differ markedly in their initial net mineralization patterns (87). Amendments high in available C (raw sludge) are biologically very active and significant quantities of nitrate-N can be lost by denitrification and immobilization soon after addition. The N in amendments that have been stabilized by removal of readily oxidizable C (digested sludge) gave net mineralization patterns similar to native soil organic N, although large amounts of N can be released from digested sludge. The N in amendments that have been stabilized by composting with wood chips is not easily mineralized. These differences among sources decrease and the mineralization rates become more alike, although the time needed to reach this point depends on the amount of amendment added (87).

TESTER, et al. (88) studied the decomposition of sludge compost in soil and found that the decompostion as determined by carbon dioxide evolution, was directly related to the amount of carbon in the compost-soil mixtures. The quantity of N mineralized ranged from 3 to 13% and the extent of N mineralized was inversely related to the C/N ratio. Ammonia evolution paralleled N mineralization. The amount of extractable P did not change during the incubation. They also found that when the pH was adjusted to 6.6, decomposition of the native soil C increased 82%, but neither soil N mineralization nor the amount of extractable P was affected (88). SOMMERS, et al. (89) have shown that denitrification and/or immobilization are major N loss mechanisms in soils treated with sewage sludge and that ammonia volatilization plays an insignificant role only. They also observed that decomposition was more a function of the sludge characteristics than the soil properties. P leaching was also minimal (89). KELLING, et al., (90) reported decomposition of liquid digested sewage sludge applied at rates from 3.75 to 60 tonnes/ha. Most of the applied inorganic N was ammonium-N and was nitrified rapidly. At sludge rates of 30 tonnes/ha or more, substantial losses of sludge-applied N occurred by leaching. The N balance indicated that considerable amounts of N may have been lost by denitrification, volatilization, or both, where more than 30 tonnes/ha were applied. Up to 50% of the applied organic N was mineralized within 3 weeks after the last sludge application, after which the mineralization rate was essentially constant at about 250 mg organic N/kg of soil/year at 60 tonnes/ha sludge rate, and 180 mg organic N/kg of soil/year at the 30 tonnes/ha rate. There was an initial immediate increase in extractable P after which it decreased, probably due to P fixation (90).

In investigations with synthetic sludge, TERRY, et al. (91) found that, after incorporation into soil, decomposition of sludge was rapid during the first 28 days after which the rate decreased. After 336 days of incubation, 46% of synthetic sludge organic carbon was evolved as carbon dioxide suggesting that one fraction of anaerobically digested sludge was readily decomposable. They also found that factors such as soil texture, pH, and moisture content had little effect on sludge decomposition rates and that decomposition was greatest in soil samples receiving surface-applied sludge and in samples incubated at high temperature (30 degrees Centigrade) as compared to samples having sludge incorporated or incubated at 21 degrees Centigrade. Increased plant nutrient availability from sludge at high temperature (35 degrees Centigrade) has also been reported by SHEAFFER, et al. (93). KLADIVKO and NELSON (76) reported a significant increase in organic carbon content in soil after sludge application at 56 tonnes/ha. SOON, et al. (67) found that $NaHCO_3$-soluble soil P increased by Ca-sludge and, to a lesser extent, by Fe-sludge additions and that sludge applications decreased ammonium acetate-extractable soil K. They also found that the ammonium acetate-extractable Mg was decreased by Ca-sludge application in some soils.

Phosphorus and sulfur transformations in soil by sludge compost application were studied by TAYLOR, et al. (94). They report that both extractable P and S are in sufficient quantities at 44.8 tonnes/ha application rate to sustain plant growth and, therefore, sewage sludge compost could be used to correct P or S deficiencies in most soils (94). Experiments by ELSEEWI, et al. (95) showed that the initial concentrations of NH_4-OAc-extractable sulfate-S in the soil were increased twofold to sevenfold by application of sludge to the soil, demonstrating that sewage sludge is a potential source of available S to plants. In studies with sewage sludge and sludge compost, EPSTEIN, et al. (75) found that nitrate-nitrogen levels were highest at the 15-20 cm soil depth but decreased sharply below this level and that the available phosphorus was in excess of that needed for good crop growth. HINESLY, et al. (79) reported constant high levels of residual total N and organic-C concentrations in sludge-amended soils for 4 years, except for a decrease in the first year after sludge application was terminated. HOHLA, et al. (96) reported organic fraction changes in soils treated with anaerobically digested sewage sludge for 6 years. They observed an increase in soil organic carbon in the top 15 cm from 0.95 to 2.29%. There were no significant changes below the 30 cm level.

The concentrations of the different sludge constituents in soil water have also been investigated. In their lysimeter studies HOHLA, et al. (96) detected increased organic fractions in the leachate water as compared to the control. Dewatered and limed sludge from a primary treatment plant applied to soils at 125 wet tonnes/ha, caused an increase in the concentrations of most ions (Cl, SO_4, Na, K, H, NO_3) except NH_4 and total-P in soil water (69). CLAPP, et al. (47) have reported nitrate-N levels within reasonable limits for soil-water nitrogen in a corn field after 3 years application of sludge, as well as low phosphate-P levels. Soil water content of ions, especially nitrate, is important with respect to groundwater contamination, and should be monitored carefully.

8. POTENTIAL PROBLEMS ASSOCIATED WITH LAND APPLICATION OF SLUDGE.

Although sludge can be a valuable resource for crop production, or land reclamation, several components of sludge are of concern. These include pathogens, nitrogen, odors, heavy metals, and toxic organic compounds. Conjecture as to the potential health effects of these materials when applied to the land has been extensive (151), while risk interpretation have been limited (5). WOLMAN (152) recently reviewed many of the problems associated with land disposal of wastes. Based on this review, it is evident that there are numerous problems associated with land application of sewage sludges, if not managed properly (8).

8.1 Potentially Toxic Elements

Potentially toxic elements in sludges are also referred to as "heavy metals" by some and "trace elements" by others. They accumulate in soils amended with sewage sludge and, in some cases, produce toxic symptoms either in vegetation grown on that soil or in animals that eat that vegetation. Potentially toxic elements include As, Al, B, Ba, Be, Cd, Cr, Co, Cu, F, Hg, Mn, Mo, Ni, Pb, Se, Ag, Zn, etc. Of these boron, cadmium, zinc, copper, molybdenum, and nickel are most likely to pose a threat of phytotoxicity or animal toxication (17).

Although residential contributions, special industrial and the general urban environment (non-point discharges) form the major sources of toxic elements to sludges, the general urban environment contributes 10% to greater than 50% more potentially toxic elements than residential areas, and residential areas often contribute more than industries. However, discharge from industries is more concentrated, and if the industrial contribution to wastewater collection system is significant, pretreatment of industrial wastes can be an efficient way of reducing potentially toxic element concentrations in municipal sludge (17).

The major proportion of the toxic element load carried by raw sewage is removed in the sludge forming processes associated with primary and secondary treatment (Fig. 21) and the major concern for toxic elements concentrations lies in sludges, not in secondary effluents (17,160). The uptake of potentially toxic elements by sludges from sewage is influenced by factors like (i) pH, (ii) ligand bonding -- chelation, (iii) retention time, (iv) toxic element concentration, and (v) ion competition for adsorption sites. These same general processes account for toxic element sorption by soils. The above factors have been discussed in detail by LOEHR, et al. (17).

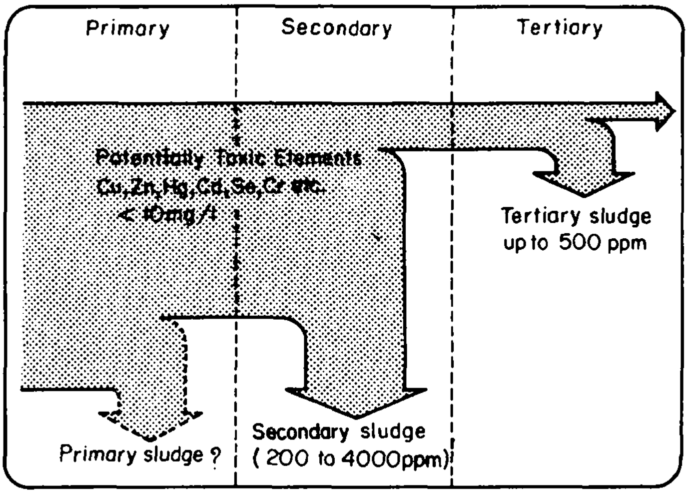


Figure 21. Fate of Heavy Metals and Other Potentially Toxic Elements in Conventional and AWT Processes (4).

After sludge application, potentially toxic elements become available for soil reactions through a variety of processes. As in the case with sludges, effective uptake of these elements in soils depends on (i) the pH of the soil solution, (ii) the availability of adsorption sites and ligand bonding, (iii) the relative competition that occurs between these elements, (iv) the rate of flow of solutions through the soil. Other significant reactions such as (i) precipitation and (ii) methylation also occur in soils. For a detailed review of these aspects, the readers are referred to LOEHR, et al. (17). Soils, except for sands, have a high capacity to retain As, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn. In situations of sludge utilization on land, essentially all of the above trace elements applied should remain within the surface meter of soil (212).

Potentially toxic elements are important because of their potential to accumulate in the soil, their phytotoxicity and their ability to enter the human food chain through crop uptake. Some mobile elements such as boron may contaminate ground water (13). Recently research in the field of land application of sludge has concentrated in assessing the availability and potential hazards to the food chain that may result from such practice (210). KIRKHAM (159) has reported and documented findings in research conducted upto 1976. JONES and LEE (153) have reviewed such findings adequately upto 1977, followed by PAHREN, et al. (154) who have summarized findings upto 1978 with special emphasis on Cd. An attempt to update this has been made in this review and is set out in Table 27.

EPSTEIN and PARR (14) have discussed the heavy metal problem vividly and they have also listed out the factors affecting the availability of heavy metals to plants, their uptake and accumulation (Table 28). According to them, land application of sewage sludge can result in soil enrichment of toxic elements, which could cause direct phytotoxic effects on plants resulting in repressed growth and yield. Potentially toxic elements may also accumulate in plant tissues, which could then enter the food chain through direct ingestion by humans or indirectly through animals. The elements in sludge of greatest concern are Zn, Cu, Ni, Mo and Cd (152). High levels of the first 3 elements in soils can cause direct phytotoxic effects on plants, resulting in repressed growth and yield. Cd poses the greatest concern to human health. Although Cd is not usually phytotoxic, it is readily absorbed by plants, can accumulate in edible parts; and enter the food chain (1,9,14). Cadmium tends to accumulate in the kidney and liver from low-level exposure and excessive intake of Cd has been associated with kidney failure, hypertension, and emphysema (9). The World Health Organization (WHO) has established that the maximum permissible level of dietary Cd should not exceed 70 microgram/person/day. LUCAS, et al. (155), BRAUDE, et al. (156), and PAHREN, et al. (154) have discussed the effects of metals on the human food chain. According to them Cd is present in significant amounts in municipal sludges and the primary source of Cd for the general population is food, with smoking as a contributor. Green vegetables accumulate more Cd than other crops. Fig. 22 shows the uptake of Cd by Swiss chard from acid and neutral soils containing various levels. PAHREN (154) outlined a method of calculating a safe level of Cd content in sludge based on these plant uptake data, estimates of acceptable Cd content of vegetables, and calculations of the amount of sludge required to provide nitrogen for corn production. The conclusion reached was that "if the Cd content is less than 60 ppm, it can be applied at maximum rates of nitrogen and produce an acceptable Cd content in vegatables. At these same nitrogen loading rates, acid soils would require sludges with less than 12 ppm" (154,155).

PAHREN (155) also stated that copper, molybdenum and selenium have caused sporadic poisoning of livestock; but the risk to humans from these 3 elements is very small by way of the human food chain. Although Ni may cause phytotoxicity to plants in acid soils and Zn is also found in large quantities in many sludges and plants, neither nickel nor zinc, however, presents a realistic hazard to humans because both are readily excreted, are of low toxicity, and are not

Table 27. Food-Chain Interactions in Sludge Amended Soils.

References	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Giordano, et al. (99).	Sewage sludge to provide 90-, 180-, and 360-kg/ha of Zn.	Sweet corn.	High forage yield. High concentrations of Zn and Cd in grain and forage.
		Bush beans.	More sensitive. Depressed yields of mature pods. Increased concentrations of Cd and Ni in vines and pods.
Mahler, et al. (100).	1% sewage sludge amended with variable amounts of $CdSO_4$.	Lettuce.	50% yield decrements for acid and calcareous soils, for soil Cd concentrations of 214 and 139 µg/g and tissue concentrations of 470 and 160 µg/g.
		Chard.	50% yield decrements for acid and calcareous soils for soil Cd concentrations of 175 and 250 µg/g and tissue concentrations of 714 and 203 µg/g.
Mitchell, et al. (101).	Sewage sludge amended with Cd, Cu, Ni and Zn. Sludge loading: 22.5 metric tons/ha.	Lettuce, wheat.	Cd, in general, most toxic followed by Ni, Cu and Zn. In calcareous soil, the latter 3 metals about equally toxic to wheat; in the acid soil, Cu about 4 times and Ni about 6 times more toxic to wheat, than Zn. Nickel more phytotoxic to lettuce and wheat grown in acid than in calcareous soil, whereas Cd, Cu and Zn toxicity depended on plant species and metal concentration range. At relatively low soil treatments, Cu and Cd more toxic to lettuce in calcareous than in acid soil.
Bingham, et al. (102).	1% municipal sludge amended with $CdSO_4$.	Alfalfa, white clover, sudangrass, tall fescue, bermudagrass.	25% depression in yield due to substrate Cd concentrations of 15, 30, 40, 95, and 145 µg/g, corresponding to clipping Cd concentrations of 9, 24, 17, 37, and 43 µg Cd/g.
Bingham, et al. (103).	1% sewage sludge enriched with Cd, Zn, Cu and Ni.	Wheat.	Significant effects on grain yield from all metal additions to acid soil and from Cd and Cu only in limed soil. Significant effects on the concentration of Cd in grain with all metals added in the limed soil, but only from Cd, Zn, and Ni on the acid soil. High correlation of soil metal additions and saturation extract metals with grain Cd concentrations.
Bingham, et al. (104).	1% sewage sludge enriched with $CdSO_4$.	Spinach, soybean, curlycress, lettuce.	Injured by soil Cd levels of 4-13 µg Cd/g soil. Leafy plants accumulated 175-354, and soybean seed 30 µg Cd/g.
		Tomato, cabbage.	No injury even at 170 µg Cd/g soils.
		Rice.	Tolerant at all levels tested.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Bingham, et al. (105).	1% sewage sludge enriched with Cd, Cu, Ni, and Zn.	Rice.	Grain yields influenced by Cu addition rate. In general, Cu content of rice grain dependent upon the Cd addition and soil pH. Maximum permissible Cd addition rate strongly pH dependent.
Hyde, et al. (106).	Digested primary sludge. Field test: up to 60 tonnes/ha.	Field corn.	In the field test, the total plant content of heavy metals increased but the corn grain not affected. In the greenhouse and laboratory tests, sludge applications to calcareous soils at up to 160 metric tons/ha had minimal impact and resulted in plant tissue concentrations similar to those found in plants grown on acid soils unamended by sludge.
Giordano, et al. (107).	Anaerobically digested sludge. (224 metric tons/ha)	Vegetables.	Soil heating up to 27°C significantly increased Cd and Zn concentrations in broccoli and potato. Liming reduced concentration of Zn and Cd in crops. Movement of Zn and Cd to a maximum soil depth of 20 to 30 cm.
Giordano, et al. (108).	Anaerobically digested sludge. 224 tonnes/ha.	Fescue.	Nitrogen fertilization did not affect the downward movement of Zn, Cd, Cr, Pb or Ni in soil but enhanced uptake because of increased growth, suggesting that heavy metal contamination of groundwater is not likely in heavy textured soils when sludge applications are accompanied by N fertilization, at least for short periods of time.
Holtzclaw, et al. (109)	Anaerobically digested sludge.	–	Findings suggest that Cd, Ni, and Zn would tend to be the more mobile trace metals in soils affected by application of the sludges investigated.
Bradford, et al. (110).	Air-dried, secondary sludge.	Bean, barley, tomato.	Adverse effects, but variable depending on the sludge source. Leaf samples contained toxic levels of B and excessive levels of one or more of the elements Cu, Mo, Ni, Co, Pb, and Cd.
Hinesly, et al. (111)	Digested sewage sludge. 262 tonnes/ha (dry weight equivalent).	Wheat, corn.	Significant increases of all elements in wheat grain except Pb, Cr, and Mn. Corn endosperm contained lower concentrations of Cd, Zn, Cu, Ni, Pb, Cr, Fe, Mn, Ca, Mg and P than whole kernels of grain. Findings useful in assessing changes in trace element contents of foods and feedstuffs.
Hinesly, et al. (112).	Anaerobically digested sludge. Max. 7-yr. accumulated appln. 374 tonnes/ha before growing season. During growing season, max. appln. 71 metric tons/ha (dry solids).	Corn inbreds.	Sludge treatments significantly increased concentrations of Zn and Cd in the plow layer of soil and in leaves of all inbreds. Inbred lines of corn differ in accumulation of Zn and Cd in leaves and grain. The capacity to accumulate Zn and Cd may be under genetic control and the mechanism for Zn and Cd appeared to be independent of each other.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings
Jones, et al. (113).	Liquid digested sludge.	Corn.	Cd and Zn increased in soil and tissue with sludge application. Cd in leaf was not affected significantly by soil pH but Cd in grain was significantly reduced above and below pH6. Below pH 6.3, Zn content in the leaf was substantially increased by increasing availability of Zn. However, above 7 when large amounts of Zn were available, increases in leaf content were not observed.
Melsted, et al. (114).	Sewage sludge to provide a maximum loading of 368.6 mt/ha.	Corn, Pheasants.	Extremely high annual soil loading rates of sludge-borne cadmium are required to produce corn grain having very high levels of Cd. In the study, Cd in corn grain had an availability to pheasants of only about 1 percent.
Sheaffer, et al. (115).	Anaerobically digested sludge. 52 and 112 tonnes/ha.	Corn, oats, wheat, rye, crimson clover and arrowleaf clover.	Significant increases in soil extractable Zn, Cu, Cd, and Ni. Zn, Cu, Ni and Cd increased in corn, legume and small grain tissue. Corn seedling Zn and Cu concentrations exceeded that in ear leaves, stover, and grain; lowest metal concentrations were found in the corn grain. With exceptions, Zn concentrations in corn tissue generally increased as soil temperature rose.
Chaney and Lloyd (116).	Anaerobically digested sludge.	Tall fescue.	Spray application markedly increased the concentrations of Fe, Cu, Zn, Pb, Cd, and Ni, in the tissue, with greater increase at high sludge rates. This suggested that adhering sludge could increase exposure of forage consumers to heavy metals.
Taylor, et al. (117).	Raw and digested sludge.	Corn.	Zinc and Copper did not move from the sludge into the surrounding soil. The increase of these metals in corn leaves was relatively low.
Chaney, et al. (118).	Mostly anaerobically digested sludge.	Soybeans, chard, orchard-grass, oat, lettuce, tall fescue.	Long term study. Crop uptake of Pb and Cu not significant. Plant levels of Ni increased only at low soil pH and high sludge-Ni contents. Soybean seed accumulates Ni when available for uptake. Zn remained unavailable for many years and grain-Zn levels increased less than foliar Zn. Sludge-applied Cd remained available to crops even after sludge use ceased. Crops differed in Cd uptake.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Dowdy, et al. (53).	Anaerobically digested sludge. I Phase: Up to 1400 tonnes/ha. II Phase: Up to 450 tonnes/ha.	Snap beans.	Zn and Cd contents of edible tissue increased as rates of sludge application increased, and reached an apparent maximum value from which they did not decrease once sludge applications ceased. Cadmium levels in edible tissue did not respond directly to sludge applications and never exceeded 0.1 μg Cd/g tissue.
Dowdy and Larson (119).	Anaerobically digested sludge. Up to 450 tonnes/ha.	Carrots, lettuce, peas, potatoes, radishes, sweet corn, tomatoes.	Potato yields not affected. Generally, metal contents of vegetative tissue were higher than those of the fruiting, root, and tuber tissue. Lettuce is an accumulator of metals, whereas potatoes and carrots are excellent non-accumulators.
Latterell, et al. (120).	Anaerobically digested sludge. Maximum single application of 450 tonnes/ha. Three annual applications: Max. 1400 tonnes/ha.	Snap bean.	A highly significant linear correlation was found between certain chemically extractable Zn and Zn concentrations in edible bean tissue, leaf tissue, and soil organic matter; extractable Cu and Cd and their concentrations in bean tissue and organic matter; extractable Ni and Pb and organic matter; and extractable Cr and organic matter.
Dowdy and Larson (121).	Anaerobically digested, air-dried sludge. Up to 30.4 tonnes/ha.	Barley seedlings.	Total uptake of Zn , Pb, Ni, and Cr was greater from sludge amended acid soil than from calcareous soil. Incubation for 1—growing degree year before crop increased the metal uptake, in general, from the incubated, acid-soil-sludge mixture than from a comparable nonincubated or alkaline mixture. Sludge applications did not affect the amount of Ca and Mg extracted, but increased Na uptake. Conversely, the Ca and Mg concentration in barley tops decreased as the Na concentration increased with added sludge. Fe in leaf tissue was greatly depressed at high sludge application rates.
Street, et al. (122).	Anaerobically digested sludge.	Corn seedlings.	Adsorption of Cd ions onto soil surface and possibly precipitation of Cd minerals indicated. At low Cd levels, solubility relationships in soils are best described by adsorption and fit the empirical Freundlich adsorption isotherm. Decreased Cd ion activity with increasing pH indicated. Extractable Cd levels in soils were highly correlated with Cd concentrations in corn seedlings.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Cunningham, et al (123).	Anaerobically digested sludge. 63 to 502 tonnes/ha (oven dry solids basis).	Corn, rye.	On all but the high pH (pH 7.8) sludge, crop yields were depressed at the high rate. The tissue concentration of metals increased with sludge rate. Phytotoxic concentrations of Cu occurred most often.
Cunningham, et al. (124).	Anaerobically digested sludge. 63 tonnes/ha (solids).	Corn, rye.	Yields decreased as the Cu and Zn content of the sludge increased. Cr may inhibit the uptake of other metals. Toxic range of Cu and Zn detected in tissue. Cd concentration of tissue increased with increasing Cu concentration in sludge.
Cunningham, et al. (125).	Anaerobically digested sludge. 63 metric tons/ha (2.8%) solids.	Corn, rye.	Indicated that caution must be used when attempting to use results of inorganic salt treatments to evaluate phytotoxicity and toxic metal uptake from sludge amended soils.
Keeling, et al. (126).	Anaerobically digested sludge. Up to 60 metric tons/ha (dry solids basis).	Rye, sorghum-sudan, corn.	In general, addition of sludge increased the concentrations of Cu, Zn, Cd, and Ni in vegetative tissue but, except for Zn, the additions had relatively little effect on the metal content of corn grain. Concentrations in all case were below phytotoxicity levels. Levels of DTPA-extractable Cu, Zn, Cd, and Ni, but not Cr, increased with sludge treatment.
Boggess and Koeppe (127).	Sewage sludge. (Secondary treated)	Soybean varieties.	Marked differences in phytotoxicity symptoms among different varieties. Good correlation suggests that data from plants grown on cadmium chloride amended soils can be used to predict soybean varietal response to Cd on sludge-amended soils.
Sidle (128).	Anaerobically digested sludge. Up to 26.96 tonnes/ha.	Mixed hardwood forest.	Heavy metal concentration in foliar samples were not abnormally higher than reported levels. Red maple accumulated Mn and Cd (to a lesser extent), while black oak accumulated Ni. Transferral of heavy metals through food chain is greatly minimized in forest sludge disposal system when compared to agriculture systems.
Sidle, et al. (129).	Sewage sludge. (Secondary treated)	–	Developed a transport model to study the movement of Cu, Zn, and Cd in a sludge-treated forest soil. Adsorption of cationic forms of these metals by the soil was described by Freundlich adsorption isotherms. Data generated by the model indicated that transport processes other than accelerated movement of chelated compounds, such as

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
			"channelization" may be involved in the field.
Sidle and Kardos (130).	Anaerobically digested sludge. Up to 26.96 m. tons/ha (total solids).	Mixed hardwood forest.	Data indicated the order of relative mobility of Cu, Zn, and Cd in soil as Cd > Zn > Cu, and that Cu applied in sludge was more extractable than the native soil Cu, Zn was only slightly more extractable, and Cd was less extractable. Of the other heavy metals, only Cr and Ni increased in the 0- to 7.5 - cm depth following sludge applications.
Silviera and Sommers (131).	Anaerobically digested sludge.	–	H_2O - soluble and exchangeable metals comprised a small percentage of the total metal concentration in the soil-sludge mixtures. The proportion of total Cu, Zn and Cd extracted by DTPA increased with time while this fraction remained constant with time for Pb. The relative amount of metals extracted by HNO_3 and DTPA were inversely related. Data indicated that forms of some metals in soils amended with sludge change with time, suggesting changes in the availability of metals to plants.
Lu, et al. (132).	Sewage sludge. (Secondary treated)	Various organisms in laboratory model ecosystem.	Studies indicated that cadmium exerted a particularly adverse effect on the various organisms in the model ecosystem and its presence in relatively high levels in sludge could pose a hazard in the food chain if applied for crop production.
Trout, et al. (133).	Anaerobically digested sludge.	Sweet corn, bluegrass.	Metal contamination of groundwater was not a problem at sludge loadings up to 65000 kg/ha on near-neutral pH soil. Cd may be the first to present such a problem. Metal ion uptake by plants grown on 65000 kg/ha sludge amended soil at near-neutral pH, is not excessive and causes no plant toxicity.
Kirkham (135).	Anaerobically digested sludge.	Barley.	At irrigation frequencies of 50 ml daily, 200 ml every 4 days, 400 ml every 8 days, and 600 ml every 12 days, Cadmium concentrations in leaves was <3 ppm and, in grain, Cd was < 0.25 ppm. Cd concentration in the roots varied (3.3 to 16.2 ppm) with Cd concentration in the sludge and increased with decreasing frequency of irrigation. Cd and Zn concentrations of the sludge crusts increased with increasing frequency of irrigation.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
De Vries and Tiller (136).	Anaerobically digested sludge.	Lettuce, onion.	Sludge applications brought about a sharp increase for most metals (Cd, Cu, Mn, Ni, Pb and Zn) in the plant material in glasshouse, whereas there was generally little increase in the concentrations in field plants, showing that glasshouse experiments, even with pots containing 16 kg dry soil, can give completely erroneous indications of the probable uptake of heavy metals by vegetables on sludge-treated soils under field conditions.
Backett, et al. (137).	Secondary digested sludge.	Barley, ryegrass, field mouse.	In addition to the Cu, Ni, Zn, Cd, Cr and Pb, commonly monitored it may be necessary to monitor Ag, Ba, Co, Sn, As, and possibly Mo, Bi, Sb, until their likely accumulations in soil can be shown to be harmless. Interactions between sludge and soil are complex. The nature of the soluble forms of heavy metals in the soil solution, and their availability to plants, changes as the interaction proceeds. The combined toxic effects of Cu, Ni and Zn in crop tissue were no more than additive. For bioassay, small animals (field mouse) were insufficiently sensitive to heavy metal accumulations.
Stucky and Newman (55).	Anaerobically digested sludge. 314 and 627 tonnes/ha.	Tall fescue, alfalfa.	Increasing rates of sewage sludge decreased the amount of Mn, Zn, Ni, and Cd accumulated in tall fescue and alfalfa in strip mine spoils. Cu accumulation was not affected by application rates. In tall fescue, per day accumulations of Mn, Zn, Cu, Ni, and Cd followed similar patterns, peaking between the 180- and 200- day growth period. This trend was observed in alfalfa for Mn and Cd; however, Zn, Cu, and Ni accumulations decreased with time. No plant toxicity symptoms were observed during the 2-year growth period.
Lagerwerff, et al. (56).	Digested secondary sludge. Mixtures of soil and sludge with up to 10% sludge (dry weight).	Rye.	Uptake of Cd, Cu, Pb, and Zn increased with sludge additions and with plant age, in the order Zn $>$ Cd $>$ Pb $\cong$ Cu. Metal uptake decreased in the order Zn $>$ Cd $>$ Pb $>$ Cu with addition of lime. Incubation between mixing and planting (0 to 7 weeks) considerably diminished Cu and Pb uptake. Observations point to organic matter complex formation in the order Cu $>$ Pb $>$ Zn $>$ Cd. The relative uptake of HCl-extractable Cd from soil was greater than that of Zn, especially

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
			upon liming, while the total uptake of these metals then decreased.
Lepp and Eardley (138).	Variable mixtures of potting medium and sewage sludge. Up to 100% sludge medium.	European Sycamore seedlings.	Increasing proportions of metal-rich sewage had no detrimental effect on plant growth. Total plant metal burdens were not excessive; the highest accumulations were found in the roots.
Furr, et al. (139).	Municipal sewage sludge 100 dry tons/acre.	Swiss chard, guinea pig.	Forty-one elements were determined in the sludge, the plant material, the liver, kidey, muscle, adrenal, and spleen tissues. Elevated concentrations of several elements found in the Swiss chard grown on the sludge-soil mixture also appeared at higher levels in certain of the animal tissues. These included antimony in adrenal, cadmium in kidney, manganese in liver tissues, and tin in several tissues. The animals showed no observable toxicological effects.
Miller and Boswell (140).	Secondary treated sludge. 11.2 and 22.4 m ton/ha.	Turnip greens, Rats.	Only liver and kidney tissue cadmium appeared to be influenced by diets derived from turnip greens produced on soil amended with industrial type sewage sludge. The cadmium content of these tissues was higher in rats fed the greens grown on sludge-treated soil than in the control.
Zwarich and Mills (141).	Digested sludge. Up to 800 tonnes/ha.	Wheat, brome-alfalfa.	No adverse effects on yields or appearance of crops noted. The tissue levels of Hg, Cr and Pb were unaffected. Cu levels in wheat kernels and straw were only slightly increased, but Cu levels in the forage crop were elevated by the sludge treatment. There was considerable increase in the Zn content of all crops, but levels were not excessive. There was a 6-fold increase in the Cd content of wheat kernels and a considerable increase in the Cd content of the forage crop, but no effect of sludge treatment on Cd levels in wheat straw.
Garcia, et al. (142).	Anaerobically digested sludge. 25 dry tons/acre.	Corn.	Generally, the highest metal concentrations occured in the leaves and roots and the lowest in the grain and cob. With the exception of Mn and Hg, metal concentrations increased in tissues as a result of sludge application. The greatest increases were for Cd where mean tissue concentrations (ppm) for unamended and sludge-grown conditions respectively were roots: 0.062, 3.63; lower stems: 0.027, 0.204; and leaves: 0.276, 1.52.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Jones, et al. (143).	Municipal digested sludge — spray applied.	Bermuda-grass, Bell rhodes-grass.	There was no preferential retention of any particular heavy metal on the foliage. Bell rhodesgrass retained more sludge than common bermudagrass due to its larger leaf blades and over-lapping sheathes. Sludge containing 4% solids was retained to a greater extent than sludge containing 2% solids. 1.25 cm of simulated rainfall removed sludge that was not allowed to dry on the leaves, whereas dried sludge could not be removed by 2.50 cm of simulated rainfall.
Baham, et al. (144).	Anaerobically digested sludge.	—	Study on the chemical mechanisms by which potentially harmful trace metals become soluble species after the incorporation of sludge into soil.
John and Van Laerhoven (145).	Primary digested sludge. Up to 100 g/kg of soil.	Lettuce, beet.	Concentrations of Cd, Zn, Pb, Cu, Ni, Mn, and Fe in lettuce, beet tops, and beet tubers were not simply or solely dependent upon the resultant sludge-borne heavy metal contamination of the soil, but a complexity of factors. Plant availability of the metals was influenced by the nature as well as the rate of sludge applied, lime regime, their interaction and the increase in soil acidity.
Williams, et al. (146).	Secondary treated sewage sludge. Up to 12, 206 and 36 kg/ha of Cd, Zn, and Cu supplied respectively.	Corn, sorghum, meadow vole.	Corn. herbage was found to contain 1.82 ppm Cd and sorghum herbage contained 4.59 ppm Cd. Significant accumulation of Cd occurred in kidneys and livers, but not in muscles of voles fed sludge-fertilized corn diets with 1.09 ppm Cd or sorghum diets with 2.76 ppm Cd. Zn and Cu accumulation in these tissues was, in most cases, nonsignificant and not associated with Cd accumulation. Daily intake of Cd was a function of the concentration of Cd and fibre in the diet. It was concluded that diets containing 1.00 ppm Cd may cause significant accumulation of Cd in animal tissues.
Sims and Boswell (147).	Industrial sewage sludge. Sludge-soil mixture of up to 10% sludge.	Wheat.	Bentonite was used to change the soil CEC and pH. Introduction of bentonite resulted in increases in CEC and pH and reductions in concentrations of heavy metals in the soil and plant. Thus soil with high CEC and pH levels may be suitable for sludge containing high metal levels.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Boswell (148).	Industrial sewage sludge. Up to 16.8 tonnes/ha for 3 applications.	Fescue.	Sludge treatment raised the Cd, Cr, Cu, Pb and Zn soil concentrations approximately 7, 3, 4, 4 and 5 times, respectively, in the surface 7.5- cm soil layer. Yield increased by approximately 30% over the control. The heavy metal content in fescue increased, the highest increase in heavy metal content of soil and plant occurred for Zn.
Andersson and Nilsson (149).	Sewage sludge. (Secondary treated)	Barley, wheat.	The extractable soil content of Hg, Zn, Cu, and Se increased more than 100 percent, and for Ni, Cr and Pb, more than 50 percent. In the vegetation, the contents of Zn, Cu, As, Ni, Cr, Pb, Hg and Mo increased by about 50% or more.
Andersen (78).	Sewage sludge. (Secondary treated)	Earthworm	Cadmium was concentrated in all species investigated whereas in some species lead uptake was lower than the others. This has significance to food chain.
Hinesly, et al. (48).	Digested sludge.	Corn.	Zn and Cu concentrations in corn were increased substantially by sludge fertilization. These metals could build up to toxic levels in the soils if sludge were applied at high rates for many years.
Hinesly, et al. (79).	Municipal sewage sludge.	Corn hybrid.	There was a substantial decrease in the Zn and Cd concentrations in the leaves and grain 3-4 years after sludge irrigation was stopped (residual effect).
Chawla, et al. (16).	Digested alum; iron or lime sludges. Up to 2100 kg TKN/ha.	Orchard grass.	Increasing rates of sludge application increased the plant tissue concentrations of Cu and Zn. Concentrations of Fe, Ni, Cr, Pb and Cd were not affected by sludge application.
Baker, et al. (150).	Sewage sludge. (Secondary treated). Up to 20 tons of dry matter/acre.	Field corn, grain sorghum.	For controlling Cd within the food chain, sludge applied as a source of nitrogen for corn on the experimental site was not supposed to contain more than 33 ± 17 ppm Cd; the labile Cd within the soil should not exceed 1 ppm.
Beaudouin, etal. (206).	Anaerobically digested sewage sludge.	Corn — soybean — — (0, 10, 20 %) sewage sludge diets, swine.	There were no increases in nine elements (Pb, Cd, Ni, Zn, Cr, Cu, Mn, Fe and Al) in sow's milk or blood; offspring of sows fed sludge diet showed increases of several elements in selected tissues at weaning and after consuming sludge diets until market weight, at 20% sludge dose.

Table 27. (Contd.)

References.	Sludge-Nature and Loading.	Test Plant (or) Animal.	Salient Findings.
Hartenstein, et al. (226).	Lab. scale: 50 g of earthworms in 400-g samples of aerobic sludge. Field scale: 1 cubic meter of sludge. Samples of worms, about 1.8 kg live weight removed every 2 weeks.	Earthworm Eisenia foetida.	In general it was found that each of the most problematical heavy metals (Cd, Ni, Pb, Zn, and Cu) can accumulate in earthworm tissues. Since these metals pose a potential for toxicity to organisms in general, animals, and animals which include earthworms in their food chain, careful thought must be exercised in the use of earthworms in sludge management.
Neuhauser, et al. (227).	Anaerobically digested sewage sludge.	Comparison of heavy metal extractability for 3 solvents.	Small, intermediate, and large amounts of heavy metals were removed, respectively, from an anaerobic digest of a sewage sludge with 2.5% acetic acid, 0.1 N HCl, and 1.0 N HCl respectively. Since it is highly likely that availability of heavy metals to plants will depend on numerous and unpredictable variables, it is proposed that until such factors are resolved, a standard extraction procedure be used by all workers on sludges and soils. This would provide a basis for comparisons of published data.

1 ton = 0.90718 tonnes

Table 28. Major Factors Affecting Heavy Metal Uptake and Accumulation by Plants (14).

Soil Factors

1. Soil pH – Toxic metals are more available to plants below pH 6.5.
2. Organic matter – Organic matter can chelate and complex heavy metals so that they are less available to plants.
3. Soil phosphorus – Phosphorus interacts with certain metal cations altering their availability to plants.
4. Cation Exchange Capacity (CEC) – Important in binding of metal cations. Soils with a high CEC are safer for disposal of sludges.
5. Moisture, temperature, and aeration – These can affect plant growth and uptake of metals.

Plant Factors

1. Plant species and varieties – Vegetable crops are more sensitive to heavy metals than grasses.
2. Organs of the plant - Grain and fruit accumulate lower amounts of heavy metals than leafy tissues.
3. Plant age and seasonal effects – The older leaves of plants will contain higher amounts of metals.

Miscellaneous Factors

1. Reversion – With time, metals may revert to unavailable forms in soil.
2. Metals – Zn, Cu, Ni and other metals differ in their relative toxicities to plants and their reactivity in soils.

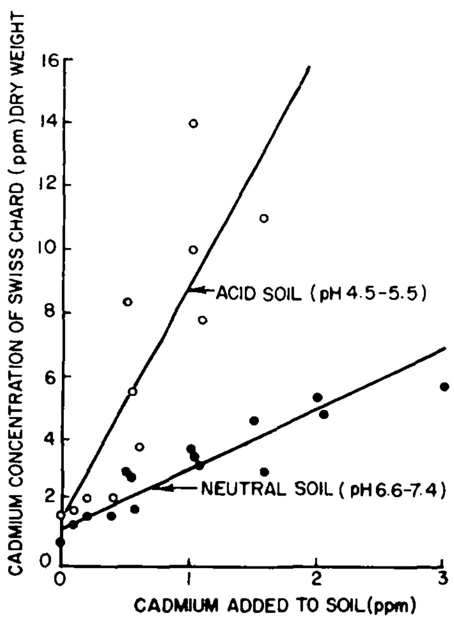


Figure 22. Relationship of Cadmium Uptake in Swiss chard to Cadmium in Soil(154).

accumulated. In general, mecury is contained in low concentrations in sewage sludges and is bound by clay or organic matter in an unavailable form and would not be a risk to human health. However, the potential hazards of methylation must be determined (17). Lead uptake by grazing animals can be a problem, but manganese, iron and aluminium are not hazardous at normal soil acidities because of their low solubility. Trivalent chromium, formed during digestion, in not accumulated by plants and is of low toxicity. Similarly arsenic is present at low levels in some sludges, but tends to be excluded from aerial plant tissues. It is also bound strongly by clay fractions of the soil (155).

CAST (46) grouped the potentially toxic elements according to the relative risk of toxicity to plants or animals as follows (46): (i) Elements posing relatively little hazard, including aluminium, antimony, arsenic, chromium, fluorine, lead, mercury, nitrogen, selenium, zinc, and (ii) Elements posing a potentially serious hazard, including boron, cadmium, copper, molybdemum, and nickel. This classification assumes that good management practices are in effect and applies to elements entering the food chain through plant roots rather than by ingestion from plant or soil surfaces by grazing animals. It is not within the scope of this review to discuss this in detail and further insight, as also some conditions which favour or hinder the availability of toxic elements to plants and animals may be obtained from CAST (46) or LOEHR, et al. (17).

Based on the sludge toxic element content, guidelines have been proposed to limit the accumulation of these elements in the soil and their uptake by plants. For example, Table 11 gives the toxic element limitations to farmlands based on soil CEC. In the Federal Republic of Germany, limits have been proposed for sludge and soil metal content (Table 29) (157) as also the maximum time of application of sludge taking into consideration plant extraction and leaching of toxic elements (158). The lower limits mentioned in Table 29 is for long term applications to land.

Table 29. Limits for Toxic Elements in Sewage Sludge and in Soils (157).

Elements	*Upper value mg/kg*	*Lower value mg/kg*	*Soil mg/kg*
Cadmium	30	10	3
Chromium	1200	600	100
Copper	1200	800	100
Lead	1200	600	100
Mercury	25	10	2
Nickel	200	100	50
Zinc	3000	2000	300

From the above review, it is evident that although the toxic effects of the trace elements themselves are understood, there is no general agreement on how to relate trace-element content of sludge and soil to human health hazards. Until such relationships are established, a major reduction of heavy metals at their source (152,208,209) and proper management and site selection (10), including application of highly contaminated sludges to non-food crops such as fibre or sod and breeding of metal tolerant crops (17), could reduce the hazard to a certain extent.

8.2 Toxic Organic Compounds

Toxic organic compounds such as PCBs (polychlorinated biphenyls) and pesticides may be present in sludges in trace amounts (9). To date there is little information available regarding organics in municipal sludges. Any organic compound discharged into a sewerage system could end up in the sludge (154). This is a potentially serious problem, since some sludges have been reported to have PCB levels up to 450 mg/kg. Generally, PCB levels are between 3 and 30 and 0.3 and 2.2 mg/kg, respectively. As PCB's are extremely toxic (PCB's have been shown to cause reproductive failures, skin lesions, and liver cancer), and they have a high potential biomagnification (magnifications as high as 2.7 x 10^{14} have been observed), the U.S. EPA has suggested a water quality standard for PCB's of one part per trillion. Hence in the USA, this standard would effectively eliminate all ocean disposal of sludges (1).

In recent years, regulations controlling the use of the "harder" pesticides, those resistant to environmental degradation, have lessened the problems of persistent pesticides in sludge. PCBs are dispersed widely in the environment and are resistent to environmental degradation. Countries like U.S. and Canada are already phasing out PCB use, so even though it may continue to be found in the environment for many years, the levels discharged to wastewater treatment plants should progressively decrease to insignificance in these countries (9,154).

Table 30. Pesticides and PCB Content of Dry Sludges (154).

Contaminant	Range (ppm)		Sludges Examined
	Min.	Max.	
Aldrin[a]	ND	16.2	5
Dieldrin[b]	<0.03	2.2	21
Chlordane[a]	3.0	32.2	7
DDT + DDD[a]	0.1	1.1	7
PCBs[c]	ND	352.0	83

Note: ND = not detected.

[a] Examined in 1971.

[b] Examined in 1971, 1972, and 1973.

[c] Examined 1971, 1972, 1973, and 1975.

PAHREN, et al. (154) have reported the pesticide and PCB content of some dry sludges (Table 30). According to them, the maximum DDT concentration found in the 7 sludges was only one-tenth the mean concentration reported in corn soils after a 6-year period of application of this insecticide. Plants sorb many organic pesticides through roots and translocate them within the plant. The factors controlling uptake are water solubility, solute concentration, size and polarity of pesticide molecules, organic matter content, pH, clay, and microbial activity of soil, with climatic factors also playing a role. According to PAHREN, et al. (154), organics are not so much a problem of uptake by plants, but of adherence to the plant. This is especially so because it appears unlikely that crops grown on insecticide-contaminated soil contain enough insecticide to be harmful to animals or men that consume the crop; on the other hand, because of the tendency of many organics to accumulate in lipid-rich tissues and fluids (milk), dairy cows should not be permitted to ingest municipal sludges applied to the surface of grazing land. One way of reducing this incidence is by incorporating sludge into soil prior to planting grasses (154).

According to DACRE (161), the dominant organic compounds are the organochlorine insecticides and the chlorinated phenolics, and because of their potential danger to human health from consumption of these chemicals (carcinogenic and teratogenic), the WHO has estimated acceptable daily intake values for many of them. Soil pollutant limitation values are being developed for some insecticides (Table 31). These values were derived for soil, but can be used to control the level of toxic chemicals in sludges before application to land (156,161).

Table 31. Soil Pollutant Limit Values (Provisional) (161).

(mg/kg Dry Soil)	
Aldrin	0.0024
Dieldrin	0.0024
Endrin	0.0048
Chlordane	0.0024
DDT (DDD, DDE)	0.0000002

JONES and LEE (153), while observing that, in general, the concentration of toxic organic compounds are considerably greater in sludge than in the wastewaters, have also pointed out that their effect has not been fully ascertained at present. They have also called for more research in this area, advocating the development of environmental chemistry-fate models designed to evalute the fate and environmental concentrations of various contaminants upon land disposal (153,162).

8.3 Pathogens

Bacteria, viruses, and parasites associated with sewage sludge may be harmful to humans when sludge is spread onto the soil. These pathogens do not enter plant tissues, but problems can result from contamination of the plant surface. If contaminated crops are consumed raw, disease transmission is possible (9). In evaluating the health risks associated with land application of sludge, the following conditions must be met to substantiate whether it is a hazard or threat to human health (160): (i) the presence of harmful agents in the wastes, (ii) that diseases or other ill effects can or do result from these agents, (iii) demonstrating the pathways by which these effects occur, and (iv) demonstrating the absence of these effects in similar unexposed environments, or their cessation when the practice is discontinued.

Table 32. Major Organisms of Health Concern in Sewage from U.S. Communities (163).

Organisms	Disease	Reservoir(s)
1. BACTERIA		
Salmonellae (Approx. 1700 types)	Typhoid Fever Salmonellosis	Man, domestic and Wild Animals and Birds
Shigellae (4 spp.)	Shigellosis (bacillary dysentary)	Man
Escherichia coli (enteropathogenic types)	Gastroenteritis	Man, domestic animals
2. ENTERIC VIRUSES		
Enteroviruses (67 types)	Gastroenteritis, heart anomalies, meningitis, others	Man, possibly lower animals
Rotavirus	Gastroenteritis	Man, domestic animals
Parvovirus-like Agents (at least 2 types)	Gastroenteritis	Man
Hepatitis A virus	Infectious Hepatitis	Man, other primates
Adenoviruses (31 types)	Respiratory disease, conjunctivities, other	Man
3. PROTOZOAN		
Balantidium coli	Balantidiasis	Man, Swine
Entamoeba histolytica	Amebiasis	Man
Giardia lamblia	Giardiasis	Man, Domestic and wild animals?
4. HELMINTHS		
Nematodes (Roundworms)		
Ascaris lumbricoides	Ascariasis	Man, Swine?
Ancylostoma duodenale	Ancylostomiasis	Man
Necator americanus	Necatoriasis	Man
Ancylostoma braziliense (cat hookworm)	Cutaneous Larva Migrans	Cat
Ancylostoma caninum (dog hookworm)	Cutaneous Larva Migrans	Dog
Enterobius vermicularis (pinworm)	Enterobiasis	Man
Strongyloides stercoralis(threadworm)	Strongyloidiasis	Man, Dog
Toxocara cati (cat roundworm)	Visceral Larva Migrans	Carnivores
Toxocara canis (dog roundworm)	Visceral Larva Migrans	Carnivores
Trichuris trichiura (whipworm)	Trichuriasis	Man
Cestodes (Tapeworms)		
Taenia saginata (beef tapeworm)	Taeniasis	Man
Taenia solium (pork tapeworm)	Taeniasis	Man
Hymenolepis nana (dwarf tapeworm)	Taeniasis	Man, Rat
Echinococcus granulosus (dog tapeworm)	Unilocular Echinococcosis	Dog
Echinococcus multilocularis	Alveolar Hydatid Disease	Dog, Carnivore

AKIN, et al. (163) have listed out the four main pathogen groups that may be present in raw sewage (Table 32). Recent reports (1,164) present data to indicate that none of the conventional sewage treatment methods (i.e. primary sedimentation, secondary treatment, anaerobic digestion, disinfection, etc.) is completely effective for pathogen destruction. Hence, it is prudent to expect hazards to crop and animals when sludge is applied to land, unless good management measures are practised. In assessing the health inplications, we must also take into account the pathways through the biosphere by which these pathogens (otherwise called nonconservative materials since they may be destroyed at several points) may be passed along to mankind, when sludges are applied to agricultural land. The major pathways are depicted in Fig. 23. (165) and the transmission can occur via the groundwater, via man coming into physical contact with the sludge, via the food chain or handling of crop grown on the land, and via aerosols (166). One point to be made when we consider the different pathways is the importance of pathogen destruction at various points. Since storage in soils allows time for destruction of pathogen, pathways which have limited storage capabilities, such as aerosols, are exceedingly important even though the mass transfer to man via this pathway is very small (165).

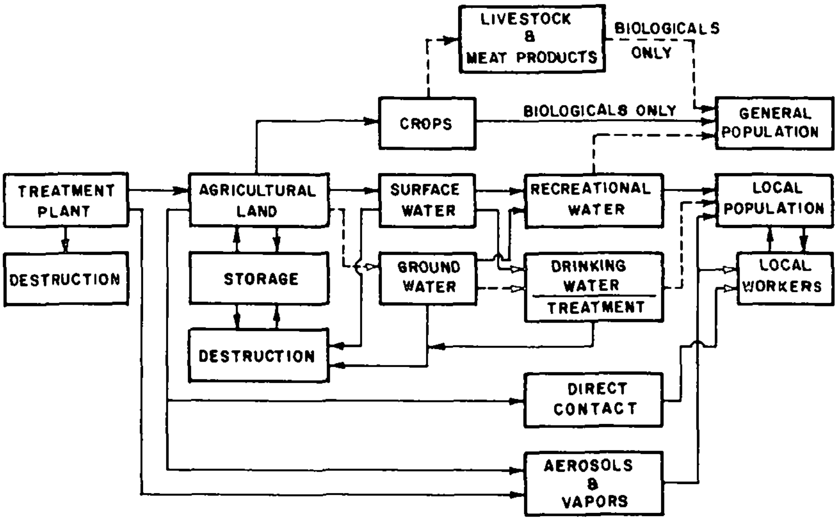


Figure 23. Major Pathways for Nonconservative Contaminant Transfer Back to Man from Land Application of Wastewater or Sludge (165).

LOEHR, et al. (17) have reviewed the present state of knowledge in pathogen implications of waste disposal on land. According to them, in evaluating health risks from land treatment, a comparison to those from conventional treatment is necessary. But evaluating the relative health risks is a difficult task and much more research is needed in this area. The general health of the community is important in determining the risk of disease from land application of wastes, in that if a disease is not present in the population, it will not be present in the population's wastes. Evaluation of the potential health hazards will rest upon our knowledge of the occurrence of pathogens in the waste and their fate during land treatment (17).

Pathogen survival and retention in the soil, and their food chain implications have been studied by many workers (213). In their treatise on land application of wastes, LOEHR, et al. (17) documented the following information. The longer pathogens survive in the soil, the greater are the chances of disease

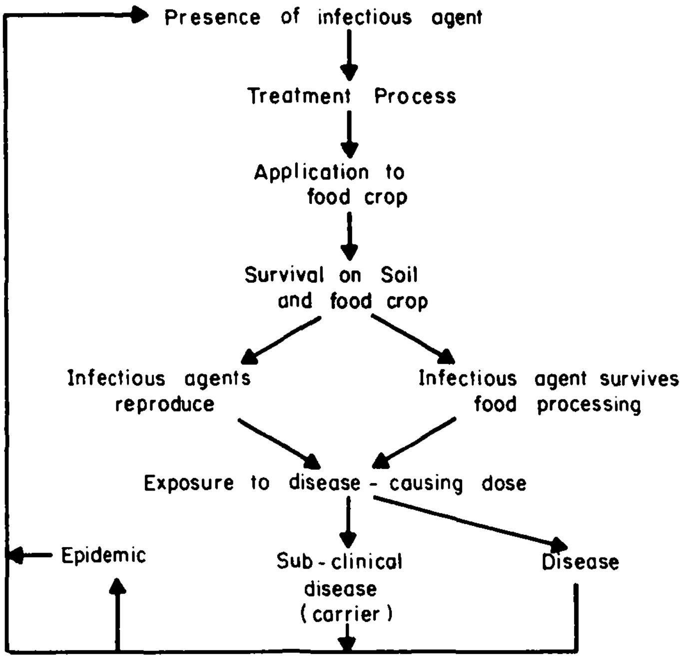


Figure 24. Pathogens Must Overcome Several Barriers in Order to Result in Disease Transmission from Infectious Agent to Healthy Populations via Land Application of Wastes (17).

transmission as they are more likely to be transferred to a susceptible host. To transmit disease, pathogens must overcome many barriers following land treatment and these are shown in Fig. 24. Pathogens in soil are destroyed by the natural environmental conditions which favour native soil organisms. Some pathogens are physically entrapped and chemically adsorbed at the soil surface, undergoing rapid die-off in the soil matrix. Bacteria appear to undergo rapid die-off in the soil matrix. In general, bacteria may survive in the soil for a period varying from a few hours to several months, depending on the type of organism, type of soil, moisture-retaining capacity of soil, moisture and organic content of the sludge, and predation and antagonism from the resident microbial flora of the soil. Table 33 lists typical survival times for certain pathogens. The moisture content, moisture-retaining capacity, pH, and organic matter content of the soil influence bacterial survival (Table 34).

Pathogens do not generally survive as long on vegetation as they do in soil because they are exposed to adverse environmental conditions like ultraviolet radiation, dessication, and temperature extremes. Information on the survival of enteric viruses in the soil, on crops, or in the groundwater is scarce and is limited to only a few types of viruses. Table 35 summarizes current thinking on virus removal from waste in various soil conditions.

There are various forces acting to retain or facilitate the movement of microorganisms through soil. Filtration by the soil at the soil-water interface is the primary means of retaining bacteria in the soil, or in some cases in an

Table 33. Survival of Selected Pathogens on Soils (Cited in 17).

Organism	Range of Survival Time
Salmonella	15-more than 280 days
Salmonella typhi	120 days
Tubercle bacilli	more than 180 days
Entamoeba histolytica cysts	6-8 days
Enteroviruses	8 days
Ascaris ova	Up to 7 years
Hookworm larvae	42 days

Table 34. Factors that Affect the Survival of Enteric Bacteria in Soil (167).

Factor	Remarks
pH	Shorter survival in acid soils (pH 3 to 5) than in neutral and alkaline soils
Antagonism from soil microflora	Increases survival time in sterile soil
Moisture content	Longer survival in moist soils and during periods of high rainfall
Temperature	Longer survival at low (winter) temperatures
Sunlight	Shorter survival at the soil surface
Organic matter	Longer survival (regrowth of some bacteria when sufficient amounts of organic matter are present)

Table 35. Several Factors Promote Virus Removal in Soil (Cited in 17).

Type of subsoil	Most desirable–deep Adequate–sandy soils; require greater depth for removal No removal–fractured layers
Soil depth	At least 5 to 10 ft to ledge or fragipan
Depth to groundwater	At least 5 ft
Application rate	Maximum rate of 0.05 to 0.10 ft/day (.6 to 1.2 in.)
Water quality	As clean as possible
Adsorption characteristics of viruses	No control possible

1 ft = 0.305 m

additional biological mat formed in the top 0.2 in. (0.5 cm) of soil. Other mechanisms that retain bacteria in the top few feet of fine soil are intergrain contacts, sedimendation and adsorption by soil particles. The soils containing clay remove most microorganisms through adsorption, while soils containing sand remove them through filtration at the soil-water interface. The movement of microorganisms through soil relates directly to the hydraulic infiltration rate and inversely to the size of soil particles and the concentration and composition of cations in the solute. Microorganisms will travel quickly through fissured zones such as limestone and basalt to the groundwater.

Table 36. Factors that Influence the Movement of Viruses in Soil (167).

Factor	Remarks
Rainfall	Viruses retained near the soil surface may be eluted after a heavy rainfall because of the establishment of ionic gradients within the soil column.
pH	Low pH favors virus adsorption; high pH results in elution of adsorbed virus.
Soil Composition	Viruses are readily adsorbed to clays under appropriate conditions and the higher the clay content of the soil, the greater the expected removal of virus. Sandy loam soils and other soils containing organic matter also are favorable for virus removal. Soils with a low surface area do not achieve good virus removal.
Flowrate	As the flowrate increases, virus removal declines, but flowrates as high as 32 ft/d (9.6 m/d) can result in 99.9% virus removal after travel through 8.2 ft (2.5 m) of sandy loam soil.
Soluble organics	Soluble organic matter competes with viruses for adsorption sites on the soil particles, resulting in decreased virus adsorption or even elution of an already adsorbed virus. Definitive information is still lacking for soil systems.
Cations	The presence of cations usually enhances the retention of viruses by soil. An increase in valence enhances retention.

Viruses are primarily removed from the waste by adsorption by the soil; thus factors enhancing adsorption increase virus removal. Factors influencing the movement and retention of viruses in soil are listed in Table 36. One area which deserves more study is pathogen survival in groundwater. Although few studies have been made on bacterial survival in groundwater, it appears that bacteria may persist in underground water for months. The extent of crop contamination depends on the type of crop and the kind of irrigation practice that is used. Irrigation of fibre crops presents the least health risk and that of food crops, especially those to be eaten raw, the greatest risk. Subsurface injection avoids direct contact between sludge and the vegatation and thereby reduces the risk of crop contamination. The survival times for some common pathogens are summarized in Tables 37 and 38. Similarly, the chances of infection for animals grazing sludge-treated areas depends on : (i) the

Table 37. Survival of Selected Pathogens on Vegetation (Cited in 17).

Organisms	Media	Survival Times (days)
Salmonella	Vegetables, fruits	3-49
	Grass or clover	12-more than 42 (and over winter)
Tubercle bacilli	Grass	10-49
Entamoeba histolytica cysts	Vegetable	less than 1-3
Enteroviruses	Vegetables	8
Ascaris ova	Vegetables, fruits	27-35

Table 38. Survival of Certain Pathogens in Soil and on Plants (9).

Organism	*Medium*	*Estimated survival time (months)*
Bacteria	Soil	Up to 6
	Vegetation	0 to 3
Enteric viruses	Soil and vegetation	0 to 3
Protozoan	Soil	Up to 6
	Vegetation	0 to 2
Parasites (ova)	Soil	Up to several years
	Vegetation	1 to 2

persistance of pathogens, (ii) the concentration of pathogens, (iii) the health of the animals, and (iv) the interval between application and grazing. Disease threat to animals from eating the crops and fodder grown on such lands can be minimized by (17): (i) allowing animals to graze only after a certain interval of time has passed following application; a number of pathogens in waste are inactivated during dessication and when exposed to sunlight, (ii) drying forage crops, and (iii) storing the dry forage before feeding it to animals.

WASBOTTEN (166) has reported that ova of the intestinal parasitic worms, particularly by Ascaris lumbricoides, are generally resistant to adverse environmental conditions and are still present in sewage sludges, creating concern with food chain transfer by the sludge-milk-human route. This is an area requiring an immediate, intensive research effort. According to PAHREN, et al. (154), although pathogenic bacteria, viruses, and parasites found in sludges raise the specter of potential health problems from plant or soil contamination, the densities of bacteria and viruses in raw waste water are greatly reduced in either the conventional sludge treatment processes or in the soil and on plants. Moreover reasonable area entry limitations and site design should prevent serious epidemiological problems from these 2 agents. On the other hand, parasitic loads in the soils may be augmented by sludge application and they are capable of prolonged survival on plants or in soil, thus posing an enchanced risk of transmission to man (154). WOLMAN (152), by citing some excellent studies on health consequences, has given a cautionary note to the people who are devoted to the cause of land application that human wastes have not given up their rich concentrations of pathogens, varying in time, place, and culture and he has also warned that to ignore them would be costly. MELNICK (162,168) also stated that since current epidemiological methods do not offer reliable means of determining whether waterborne viral outbreaks have occurred, it is impossible to ascertain the risk from viruses associated with the land application of wastes. He has suggested total elimination of all viruses from wastes applied to land. MOORE, et al., (169) have warned that even digested sludges will carry infectious virions into the soil, where their survival is a function of regional or local climatic conditions. They have suggested reasonably long detention times and high temperatures for digestion. MOORE, et al. (217) have also stressed the need for information on the survival and transport of viruses in various soil systems.

On the other hand, there have also been optimistic reports on pathogen reduction in soil. According to TAYLOR, et al. (117), although low levels of fecal coliforms were present in sludge applied to land, none were found in the soil surrounding the sludge. It has been suggested that ammonia generated on dissociation of NH_4^+, may be important in reduction of human pathogens. In another report (170) it has been stated that well-stabilized sludges, accomplished by anaerobic digestion, extended aeration or extended lagooning, are generally free of pathogens. If sludges are not well treated, there is always a danger of soil and crop contamination by pathogens which may eventually be transmitted to humans. Such food chain hazards by virus, bacteria and parasites have been addressed by numerous authors (156,171-173).

Table 39. Factors that Affect the Survival and Dispersion of Bacteria and Viruses in Waste Aerosols (167).

Factor	Remarks
Relative humidity	Bacteria and most enteric viruses survive longer at high relative humidities, such as those occurring during the night. High relative humidity delays droplet evaporation and retards organism die-off.
Wind speed	Low wind speeds reduce biological aerosol transmission.
Sunlight	Sunlight, through ultraviolet radiation, is deleterious to microorganisms. The greatest concentration of biological aerosols from waste occurs at night.
Temperature	Increased temperature can also reduce the viability of microbial aerosols mainly by accentuating the effects of relative humidity. Pronounced temperature effects do not appear until a temperature of 80°F (26.7°C) is reached.
Open air	It has been observed that bacteria and viruses are inactivated more rapidly when aerosolized and when the captive aerosols are exposed to the open air than when held in the laboratory.

Another area which needs research is the survival of pathogens in aerosols. Table 39 summarizes the survival of pathogens in aerosols. Bacterial and viral pathogens in aerosols can be inhaled by humans, causing infection. At least some potential health effects are related to the production of aerosols; however, these deleterious effects have yet to be fully established. To reduce or eliminate these possible effects, the following practices are recommended (17,166): (i) creating buffer zones, (ii) controlling sprinkling operations to minimize the production of fine droplets, (iii) eliminating sprinkling during high winds, (iv) restricting sprinkling to daylight hours, (v) decreasing nozzle pressure, (vi) aiming the nozzles downwards, (vii) planting hedgerows on buffer zones. High rate of evaporation of aerosols results in die-off of many pathogenic organisms. It may also take fewer pathogens to cause infection when inhaled in aerosols than when ingested directly. Although aerosols are generated from conventional treatment plants as well as spray irrigation, there have been no reports of disease transmitted from these plants (17,174,230).

Since insects and rodents might transmit bacteria and virus from sludges, their control on a land application site is critical. Although there is no conclusive evidence that insect or rodent transmitted diseases increase in such sites, more investigation is needed to evaluate this problem. However, it is known that the wetter conditions and the increased vegetative cover increase the potential for the number of insects and rodents. Unless properly designed and managed to eliminate ponded water, mosquito propagation could be severe on such sites. Conventional methods of control may be utilized to control these pests (17,166).

There are reports that nuclear reactor wastes are being used as a radiation source to kill pathogens in sewage sludge in Sandia Laboratories, New Mexico (175,218). This might add a new dimension to utilization of sewage sludge for land application.

Inspite of the possibility of communicable disease transmission from land disposal of municipal sludges, there is no epidemiologic evidence, to date, suggesting that this practice has resulted in actual human illness where sludge has been properly treated and applied (9,154). Some workers like AKIN, et al. (163) are convinced that since there is no evidence for disease transmission from the application of treated sludge to land, and because it is unrealistic to insist upon pathogen-free waste, land application of sludge can be considered an acceptable risk unless future epidemiological evidence indicates the contrary.

As mentioned above, if sewage sludges receive adequate pretreatment, and are applied to land at acceptable rates and in a manner in which rapid percolation and runoff are minimized, the potential for transmission of disease is negligible (174). DUDLEY, et al. (176) recently enumerated potentially pathogenic bacteria from sewage sludges and they are of the opinion that land disposal of sludge should be coupled with land use limitations for such sites. According to them, land disposal of sludge is reasonable for food crops that undergo heat processing, for fibre crops, or for forest products. They recommend that agricultural and recreational lands should not be utilized as application sites for primary and digested sludge disposal, unless the residual has been further treated by composting, irradiation, or pasteurization (176). The following general precautions should be borne in mind to reduce the possible transmission of disease agents (177): (i) Wastes must be adequately treated to reduce pathogen levels to as low numbers as possble, (ii) Do not apply sludges to crops that are to be eaten or grazed unless adequate time is allowed for die-off, or the produce is to be thoroughly cleaned and sanitized, (iii) Limit the quanties of waste added to a single site to reduce probability of pathogen buildup, (iv) Have adequate knowledge of the geology and hydrology of a receiving field so that groundwaters are protected and run-off to surface waters is minimised, (v) Avoid high-density population centres (and perhaps even high-density animal areas) where vectors such as wind, insects, and rodents may serve as the carriers of the infectious agents, (vi) Maintain a high level of immunity, where it is possible, in the human and animal population to reduce the epidemiologic hazards, and (vii) Health care in the area, both animal and human, is essential to treat the infected and to reduce the potential for high levels of infections organisms in the wastes and the soils receiving them.

8.4 Nitrogen

The chief problems with nitrogen in sludge include the hazard of high nitrate concentrations in crops, drainage water, and groundwater, including the possibility of nitrosamine formation (17). There have been reports of threat from nitrate pollution occuring due to sludge application on land (128,133). Cattle can also be affected by grass tetany and in infants high concentrations of nitrates in drinking water can cause "blue babies" disease or methemoglobinemia (1,17).

Evidence that N in sludge presents either more or less hazard than equivalent amounts of nitrifiable or plant-available N from inorganic source is lacking. Good management aims to provide needed amounts of N to the crop, avoid production of crops high in nitrate, and to minimize nitrate in water. Growing corn or other cereals for grain reduces the hazard from nitrate crops, since cereal seeds have not been found to contain high levels of nitrate even when the leaves and stems contain hazardous levels. As we have seen earlier, nitrogen is the limiting factor in most land application situations.

8.5 Odor

Land application of sludge, if not properly managed, poses a serious potential for offensive odor nuisances (166). The problem originates at the point of initial sludge handling and after the sludge is applied to land, the odor potential can extend over a long period. In evaluating such a problem, a case-by-case study is necessary. Sludges should be incorporated into the soil prior to any rainstorm. Subsurface injection of liquid sludge has been found to be successful in controlling odor. Other methods are heat treatment followed by sludge dewatering, composting, chemical treatment with high concentrations of lime and chlorine, and pressure filtration of sludge cake. The application of well-digested, drying bed sludge to land is probably the most economical and normally odor-free method for small facilities (166).

Odor problems can be kept to a minimum by means of proper sludge digester operation, sludge handling techniques, and land management at the application site (166). Because the presence of odors near application sites is almost inevitable at some point, the most effective means of obtaining public acceptance and support of land application of sludge may be through public involvement and education (9).

WOLMAN (152) in his excellent summary on the public health aspects of land application has pointed out, on the basis of the experience gathered over more than a century, that application of waste to land is a practicable method of disposal, provided: (i) It is carefully, efficiently and continuously managed, (ii) An appropriate site, characterised by equally appropriate soil permeability and porosity, is within economic transport distance, (iii) Provision for hold-over storage, during wet weather, is afforded, (iv) Crop production is restricted to those not eaten raw, (v) Monitoring is exercised to prevent undue hazard to groundwater or drainage effluent, (vi) Potential hygienic risks are detected and controlled (the record is clear than this procedure is wholly practicable), and (vii) The process is cost effective.

Some management, economic, legal and social aspects of land application of sludge will be covered briefly in the following sections.

9. PREAPPLICATION REQUIREMENTS AND REGULATIONS.

Land application of sludge, if properly managed, may provide significant benefit and may be an environmentally acceptable method of disposal. If improperly managed, it can create a potential threat to the human food chain through the entry of toxic elements, compounds, and pathogens into the diet. In the developing countries, land application of nightsoil is widely prevalent but there are as yet no official guidelines to control and regulate this application. On the other hand, developed countries have issued detailed preapplication strategies and regulations which have to be strictly followed by those in the profession. The U.S. regulations are repeated here to illustrate such preapplication requirements for land application of sludge:

As seen earlier, in the U.S. the preapplication requirements have been well clarified by the US Environmental Protection Agency in the criteria and regulations that it has developed for solid waste disposal facilities and practices (178). The Agency believes that even food-chain land application practices which comply with the preapplication strategies mentioned below will pose no reasonable probability of adverse effects on public health or the environment.

The preapplication requirements in the U.S., as related to diseases, fall into two categories in general (178) : (i) Processes to significantly reduce pathogens, and (ii) Processes to further reduce pathogens.

(A) Processes to Significantly Reduce Pathogens.

(i) Aerobic digestion: The process is conducted by agitating sludge with air or oxygen to maintain aerobic conditions at residence times ranging from 60 days at 15 degrees Centigrade to 40 days at 20 degrees Centigrade, with a volatile solids reduction of at least 38 percent.

(ii) Air Drying: Liquid sludge is allowed to drain and/or dry on under-drained sand beds, or paved or unpaved basins in which the sludge is at a depth of nine inches (23 cm). A minimum of three months is needed, two months of which temperatures average on a daily basis above 0 degrees Centigrade.

(iii) Anaerobic digestion: The process is conducted in the absence of air at residence times ranging from 60 days at 20 degrees Centigrade to 15 days at 35 to 55 degrees Centigrade with a volatile solids reduction of at least 38 percent.

(iv) Composting: Using the within-vessel, static aerated pile or windrow composting methods, the sludge is maintained at minimum operating conditions of 40 degrees Centigrade for 5 days. For four hours during this period the temperature exceeds 55 degrees Centigrade.

(v) Lime stabilization: Sufficient lime is added to produce a pH of 12 after 2 hours of contact.

(vi) Other methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

(B) Process to Further Reduce Pathogens.

(i) Composting: Using the within-vessel composting method, the sludge is maintained at operating conditions of 55 degrees Centigrade or greater for three days. Using the static aerated pile composting method, the sludge is maintained at operating conditions of 55 degrees Centigrade or greater for three days. Using the windrow composting method, the sludge attains a temperature of 55 degrees Centigrade or greater for at least 15 days during the composting period. Also, during the high temperature period, there will be a minimum of 5 turnings of the windrow.

(ii) Heat drying: Dewatered sludge cake is dried by direct or indirect contact with hot gases, and moisture content is reduced to 10 percent or lower. Sludge particles reach temperatures well in excess of 80 degrees Centigrade, or the wet bulb temperature of the gas stream in contact with the sludge at the point where it leaves the dryer is in excess of 80 degrees Centigrade.

(iii) Heat treatment: Liquid sludge is heated to temperatures of 180 degrees Centigrade for 30 minutes.

(iv) Thermophilic aerobic digestion: Liquid sludge is agitated with air or oxygen to maintain aerobic conditions at residence times of 10 days at 55-60 degrees Centigrade, with a volatile solids reduction of at least 38 percent.

(v) Other methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

In addition, any of the processes listed below, if added to the processes described in Section (A) above, further reduce pathogens. Because the processes listed below, on their own do not reduce the attraction of disease vectors, they are only add-on in nature.

(vi) Beta ray irradiation: Sludge is irradiated with beta rays from an accelerator at dosages of at least 10 megarad at room temperature (ca. 20 degrees Centigrade).

(vii) Gamma ray irradiation: Sludge is irradiated with gamma rays from certain isotopes, as Cobalt 60 and Cesium 137, at dosages of at least 1.0 megarad at room temperature (ca. 20 degrees Centigrade).

(viii) Pasteurization: Sludge is maintained for at least 30 minutes at a minimum temperature of 70 degrees Centigrade.

(ix) Other methods: Other methods or operating conditions may be acceptable if pathogens are reduced to an extent equivalent to the reduction achieved by any of the above add-on methods.

Based on these two processes, regulations to protect against diseases have been drawn up as follows (178):

(a) Disease Vectors.

The facility or practice shall not exist or occur unless the on-site population of disease vectors is minimised through the periodic application of cover material or other techniques as appropriate so as to protect public health.

(b) Sewage Sludge.

A facility or practice involving disposal of sewage sludge shall not exist or occur unless in compliance with the following:

(i) Sewage sludge that is applied to the land surface or is incorporated into the soil is treated by a Process to Significantly Reduce Pathogens prior to application or incorporation. Public access to the facility is controlled for at least 12 months, and grazing by animals whose products are consumed by humans is prevented for at least one month. (These provisions do not apply to sewage sludge disposed of by a trenching or burial operation).

(ii) Sewage sludge that is applied to the land surface or is incorporated into the soil is treated by a Process to Further Reduce Pathogens, prior to application or incorporation, if crops for direct human consumption are grown within 18 months subsequent to application or incorporation. Such treatment is not required if there is no contact between the sludge and the edible portion of the crop; however, in this case the sludge is treated by a Process to Significantly Reduce Pathogens, prior to application; public access to the facility is controlled for at least 12 months; and grazing by animals whose products are consumed by humans is prevented for at least one month. If crops for direct human consumption are not grown within 18 months of application or incorporation, the requirements of the above paragraph (b) (i) apply.

In the U.S., any owner or operator of a publicily owned treatment works must comply with the above-mentioned regulations when disposing of sludge on the land.

10. MANAGEMENT AND MONITORING AT LAND APPLICATION SITES.

10.1 Management Aspects

In an earlier section it was mentioned that the annual application rate is usually based on nitrogen sufficiency for crop growth and that long-term quantity of sludge applied to any one site is based on the type and quantity of metals present in the sludge. This section will consider a few management aspects for land application of sludge. However, it must be borne in mind that no one proposal can be recommended for all situations - the design and management of each site will be unique. Field trials may be conducted to ensure the best system for a particular area, posing minimum potential hazards and maximum potential benefits. COKER (179) has reported on the design and establishment of such field experiments for conditions in England. Similar trials may be conducted in other countries.

MILLER (44) has outlined some management considerations for sludge application to agricultural land as follows:

(a) Soil Management:

(i) Site Selection: As mentioned already, of primary importance to the success of a system is the establishment and maintenance of a pH more than 6.5 to restrict plant uptake and accumulation of metals as well as their downward mobility in the soil. Liming helps in attaining this if the soil is acidic. The soil CEC, organic matter content, the presence of hydrous oxides of iron, aluminium, manganese, and the phosphorus content also influence the chemistry and availability of metals in soils. Soil drainage characteristics influence the timing and method of sludge application, tillage, planting, and harvesting operations after sludge additions.

(ii) Fertility Considerations: In general, it has been estimated that 25-50% of the ammonium will be lost if sludge is surface-applied and if it is injected into the soil or incorporated into the soil immediately after surface application, most of the ammonium will be retained. Sludges contain considerably more phosphorus relative to the nitrogen needs of most crops, but unless very high amounts are applied, the soil will immobilize excess phosphorus and there is no problem for many years in general. Potassium is very low in sludges and poses no hazard.

(iii) Runoff Control: Where sloping land is employed for sludge application, methods of application other than surface application must be considered. Diversions or earthern barriers may also be used to contain runoff temporarily, and prevent sludge from reaching water courses. Conservation practices such as reduced tillage systems, terraces, strip cropping, and retention of crop residues on the soil surface wherever possible may also be used to minimise erosion.

(b) Crop Selection:

If there are no limitations in the selection of plant species, it is advantageous to maintain the normal cropping patterns found in the community. In the case of monoculture, an additional crop or crops may be employed to increase the opportunity of applying sludge during a variety of seasons.

(c) Timing of Operations:

The timing of sludge applications to land is independent of climate, soil properties, the crop, and the tillage, planting, and the harvesting procedures employed. Frozen soils or snow cover make sludge applications impractical or environmentally unsound. Storage facilities may be needed in such cases. The growing season of plants and the rate of decomposition of sludge organics in soil may also be influenced by temperature. Sludge should not be applied with heavy equipment to wet soils. Rainfall distribution also influences the amount of sludge storage required by a municipality. Scheduling sludge application as well as determining the ease and timeliness of all tillage, planting, and harvesting operations require that soil properties are optimum. Well-drained soils must be chosen to produce a minimum delay for all important operational procedures of the system. A careful choice of crop enables varying the time periods during which sludge can be applied to land.

(d) Other Considerations:

Any potential danger of retardation of seed germination and early plant growth can be reduced by applying the sludge 2-3 weeks before planting, by thorough mixing of the sludge in the tilled soil layer, or a thorough irrigation prior to planting. Tomato seeds survive waste treatment and grow profusely in sludge-treated soils. Normal weed and pest control practices may be adopted for crops. It is not advisable to apply sewage sludges directly on leaves of growing plants unless the sludge solids are washed off by irrigation water. Liquid sludge may be applied to row crops during the growing season by gravity irrigation techniques, by tank wagons, or by overhead irrigation systems equipped with drop hoses between rows. In the case of forage crops, sludges may be applied during the season if applied prior to spring growth, after dormancy, or immediately after cutting and before significant new growth begins.

Good management is the key to a successful land application program for sewage sludges which ensures that potential hazards are minimized and potential benefits are maximized from a technical standpoint. Good management is also critically important in achieving social acceptance - so as not to create public nuisances - for this alternative of ultimate sludge disposal (8).

10.2 Monitoring at Sludge Application Sites.

According to BLAKESLEE (180), monitoring includes observation of system performance, checking the quality of affected natural systems, and observing and recording environmental impacts as quality changes occur. LOEHR (181) has pointed out the environmental concerns resulting from inadequate management at land application sites as follows : (i) food chain (metals, toxic organics), (ii) odors, (iii) erosion and runoff, (iv) leachate, and (v) pathogens.

According to LOEHR (181) the primary environmental concerns related to land application of sludge relate to potential contamination of the food chain and pollution of surface and groundwaters. In additon, there can be public health, odors, and nuisance problems. Sludge applications on the land can generate serious odors if the site and application rates are not properly managed. Odor problems begin at the point of initial sludge handling and continue after the sludge is applied to the land. The degree of offensive odor depends upon the type and nature of the sludge, any pretreatment or dewatering prior to disposal, and how it is managed after it is applied.

The sludge should not be allowed to stand in liquid pools for any length of time and should be incorporated in the soil when applied or shortly after application. Tank trucks transporting the sludge to the application site should not leak and should be clean.

The potential for pathogen transmission exists, and if the land application is done improperly, it can cause a public health problem. The transmission can occur through groundwater, surface runoff, aerosols formed during application and direct contact with the sludge or raw crops from the application site. Because bacteria, viruses, and parasites do not enter plant tissues, transmission of pathogens via crops grown on the land application site results from contamination of the plant surface. If contaminated crops are consumed raw, disease transmission is possible. Disease transmission due to application of sludge onto farmland is rare. Reported outbreaks of disease have generally been the result of application of inadequately treated sludges to truck gardens or other crops which were eaten raw.

As seen already in Section 8.3, pathogens in land applied sludge usually will die rapidly depending upon temperature, moisture, and exposure to ultraviolet light. Typical survival times in soil and on plants are noted in Table 38.

In general, pathogen survival is shorter on plant surfaces than in the soil. To prevent disease transmission, it is recommended that sludge not be applied to land during a year when crops are to be grown for raw consumption. Where humans have little physical contact, the presence of pathogens may be of less concern. The soil can filter and inactivate bacteria and viruses. Sludge application methods and rates should take advantage of the soil to reduce public health concerns.

Another potential constraint is the possibility of increased nitrate concentrations in the ground water and transmission of heavy metals and toxic organics through the food chain. Certain metals also are known to be toxic to specific crops. In the U.S., most states have guidelines and regulations controlling the quantity of metals and toxics that should be applied to land. In addition, as seen in Section 3, the Environmental Protection Agency in the U.S. has promulgated criteria for solid waste disposal facilities and practices (178) which include criteria for the application of sludge to land used for the production of food chain crops.

Two interrelated key factors in the avoidance of adverse environmental impacts from sludge land application systems are the sludge application rate and the land area that is used. Many factors determine the required land area such as sludge characteristics, characteristics of the soil, climate, wastewater, and crop. These should be evaluated using site specific information. The limiting parameter approach described in Section 3.4 and illustrated in Fig. 10 may be used to determine the land area required.

The basic concept inherent in the limiting parameter approach is to use site specific data to meet the desired groundwater quality, and calculate the loadings accordingly. The concept uses soil loading criteria which incorporate specific information about the sludge characteristics, soil characteristics and the crop for the design of an environmentally sound land application system for sludges.

There have been both concern (182) as well as optimistic reactions (47,183,184) regarding the potential hazards of land application of sludge. It will suffice to say that land application can be a practicable method of sludge disposal provided that the system is carefully, efficiently a d continuously managed, crops are restricted to those not eaten raw, and monitoring exists to detect and control potential public health threats.

Monitoring at land application sites serves several important functions (17): (i) It provides data to prove that the land application system complies with standards of water quality and environmental safety, (ii) It reveals any inadequacies in the original design of the system, (iii) It provides data which can be used in the design of future land application system, and (iv) It provides information needed for careful day-to-day management of the land application system. An environmental assessment of municipal sludge utilization for land application has been reported by OTTE and LaCONDE (185). This reveals numerous facts about such existing sludge land application systems in the U.S.

According to the U.S. Environmental Protection Agency (45), any sludge application site must have a monitoring program for observing and evaluating systems performance. Sludge composition, groundwater quality, soil properties, and plant composition would be monitored in an optimum sampling program. The type of monitoring program is defined by the size and purpose of the project. Large-scale land application programs would require extensive monitoring at high frequency, while with smaller projects less extensive and frequent monitoring would suffice (186). The monitoring plan should also be specifically designed for local conditions including site and sludge characteristics, proposed rate of application, crops to be grown, etc. (187).

A few more details regarding monitoring will be presented here and a major portion of the material is adapted from the EPA manual "Principles and Design Criteria for Sewage Sludge Application on Land" (45).

(A) Periodic Sludge Analysis:

Periodic sludge analysis confirms that the waste is acceptable and provides a record of nutrient and metal additions to soils. The frequency of sampling will depend upon sludge characteristics and sludge variability. The recommended analysis and suggested analytical methods are shown in Table 40. All composition data must be expressed on an oven-dry solids basis, since the solids content of sludges varies from batch to batch.

Table 40. Methods for Sludge Analysis (Cited in 45).

Parameter	Suggested method
Percent solids..................	Drying at 105°C for 16 hrs.
Total N (nitrogen)...........	Micro-Kjeldahl and S.D.[a]
NH_4^+-N (ammonium)......	Extraction with potassium chloride and S.D.[a]
NO_3^--N (nitrate)...........	Extraction with potassium chloride and S.D.[a] after reduction
Total P (phosphorus)......	Nitric acid-perchloric acid digestion and colorimetry
Total K (potassium)........	Nitric acid-perchloric acid digestion and *flame photometry*
Copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), and cadmium (Cd).	Nitric acid-perchloric acid digestion and atomic absorption[b]
Stable organics[c]..............	Variable

[a] S.D., steam distillation and titration of distillate with standard sulfuric acid. Colorimetric procedures can be used for N species.

[b] Background correction (e.g., deuterium or hydrogen lamp) may be needed for cadmium and nickel.

[c] Optional and site specific.

(B) Site Analysis:

When sludges are applied at a rate equal to crop nutrient requirements, no special monitoring is necessary, but when it is applied at rates exceeding recommended plant nutrient requirements or heavy metal limits, a special monitoring program will be required.

(a) Soils.

Initial monitoring of soils provides a reference datum specifying original conditions as well as necessary or tolerable sludge constituent additions which can be made. Subsequent soil analyses indicate contaminant buildups, efficacy of plant uptake and removals, evenness of sludge application and other environmental impacts. Soil analysis also allows calculation of sludge loading rates and provides estimates of remaining site life. Standardised analytical procedures for sludge amended soils have not yet been established but the analytical procedures used for agricultural or forested soils are generally sufficient.

Heavy metal and nitrate analysis should be performed for both agricultural and nonagricultural systems. Additional analyses of P, K, pH, CEC, organic matter would be required to provide information for fertilizer recommendations and site management. If the movement of nitrates into groundwater is monitored, soil cores to a depth of 3 to 5 feet (0.9 to 1.5 m) may be obtained at the end of the growing season and each 1 foot increment may be analysed for ammonium and nitrates.

(b) Groundwater and Runoff.

Monitoring wells may be designed and located to meet the specific geologic and hydrologic conditions at each site. Consideration should be given to the following aspects (180): (i) Geologic soil and rock formations existing at the specific site, (ii) Depth to an impervious layer, (iii) Direction of flow of groundwater and anticipated rate of movement, (iv) Depth of seasonal high water table and an indication of seasonal variations in groundwater depth and direction of movement, (v) Nature, extent, and consequences of mounding of groundwater which can be anticipated to occur above the naturally occurring water table, (vi) Location to nearby streams and swamps, (vii) Potable and nonpotable water supply wells, and (viii) Other data as appropriate.

Background data should be obtained from wells in the same aquifer beyond and within the anticipated area of influence of the system and be compared with subsequent data to assess the impact. In addition to background sampling, ground water samples should be taken at perimeter points in each direction of groundwater movement from the site. Perimeter wells must intersect flow lines and must be of optimum depth. Samples may be collected monthly during the first two years of operation. Later on they may be modified. The following sampling procedures may be employed: (i) A measured amount of water equal to or greater than three times the amount of water in the well and/or gravel pack should be exhausted from the well before taking a sample for analysis; in the case of very low permeability soils, the well may have to be exhausted and allowed to refill before a sample is collected, (ii) Pumping equipment should be thoroughly rinsed before use in each monitoring well, (iii) Water pumped for each monitoring well should be discharged to the ground surface away from the wells to avoid recycling of flow in high permeability soil areas, and (iv) Samples must be collected, stored, and transported to the laboratory in a manner to avoid contamination or interference with subsequent analysis.

Water samples collected from sludge application sites should be analyzed for the following: (i) chloride, (ii) conductivity, (iii) pH, (iv) total hardness, (v) alkalinity, (vi) total nitrogen, (vii) ammonia nitrogen, (viii) nitrate nitrogen, (ix) total phosphorus, (x) methylene blue active substances, (xi) total organic carbon, and (xii) heavy metals or toxic substances where applicable.

(c) Vegetation.

Plant tissue composition is a sensitive and meaningful indicator of impacts, provides useful information on plant nutrient deficiencies and toxicities, and indicates potential health hazards in food-chain crops. The basic principles underlying plant tissue sampling are common to both forestry and agricultural species, but specific methodologies are unique to both practices. A summary of sampling techniques for agricultural crops is presented in Table 41. Although the use of vegetable crops is not recommended on soils treated with sludge, diagnostic tissues for these crops are also presented. Sampling the mature grain or forage is the preferred method of monitoring from the point of view of metal impact on the human food chain. The major emphasis is placed on analysis of zinc, copper, nickel, cadmium and lead. So far limits have

Table 41. Suggested Procedures for Sampling Diagnostic Tissue of Crops (Cited in 45).

Crop	Stage of growth[a]	Plant part sampled	Number plants/ sample
Corn	Seedling	All the above ground portion.	20-30
	Prior to tasselling	Entire leaf fully developed below whorl	15-25
	From tasselling to silking	Entire leaf at the ear node (or immediately above or below).	15-25
Soybeans and other beans	Seedling	All the above ground portion.	20-30
	Prior to or during early flowering	Two or three fully developed leaves at top of plant.	20-30
Small grains	Seedling	All the above ground portion.	50-100
	Prior to heading	The 4 uppermost leaves	50-100
Hay, pasture or forage grasses	Prior to seed emergence	The 4 uppermost leaf blades.	40-50
Alfalfa, clover and other legumes	Prior to or at 1/10 bloom	Mature leaf blades taken about 1/3 of the way down the plant.	40-50
Sorghum-milo	Prior to or at heading	Second leaf from top of plant.	15-25
Cotton	Prior to or at 1st bloom, or at 1st square	Youngest fully mature leaves on main stem.	30-40
Potato	Prior to or during early bloom	3rd to 6th leaf from growing tip.	20-30
Head crops (e.g., cabbage)	Prior to heading	1st mature leaves from center of whorl.	10-20
Tomato	Prior to or during early bloom stage	3rd to 4th leaf from growth tip.	10-20
Beans	Seedling	All the above ground portion.	20-30
	Prior to or during initial flowering	2 or 3 fully developed leaves at the top of plant.	20-30
Root crops	Prior to root or bulb enlargement	Center mature leaves.	20-30
Celery	Mid-growth (12-15" tall)	Petiole of youngest mature leaf.	15-30
Leaf crops	Mid-growth (12-15" tall)	Youngest mature leaf.	35-55
Peas	Prior to or during initial flowering	Leaves from 3d node down from top of plant	30-60
Melons	Prior to fruit set	Mature leaves at base of plant on main stem	20-30

[a] Seedling stage signifies plants less than 12 inches tall.

1 in = 2.54 cm

not been set for allowable heavy metal concentrations in plant tissues consumed by humans or animals.

It is to be expected that, as research proceeds, the kind of guidance needed to develop effective but reasonable monitoring programs will gradually unfold. However, the prognosis at present is that little monitoring of soils and crops would be needed if sludges were monitored, heavy metal levels were controlled, and good soil and crop management practices were followed (46).

11. ECONOMICS AND MARKET CONSIDERATIONS.

11.1 Economics of Sludge Land Application

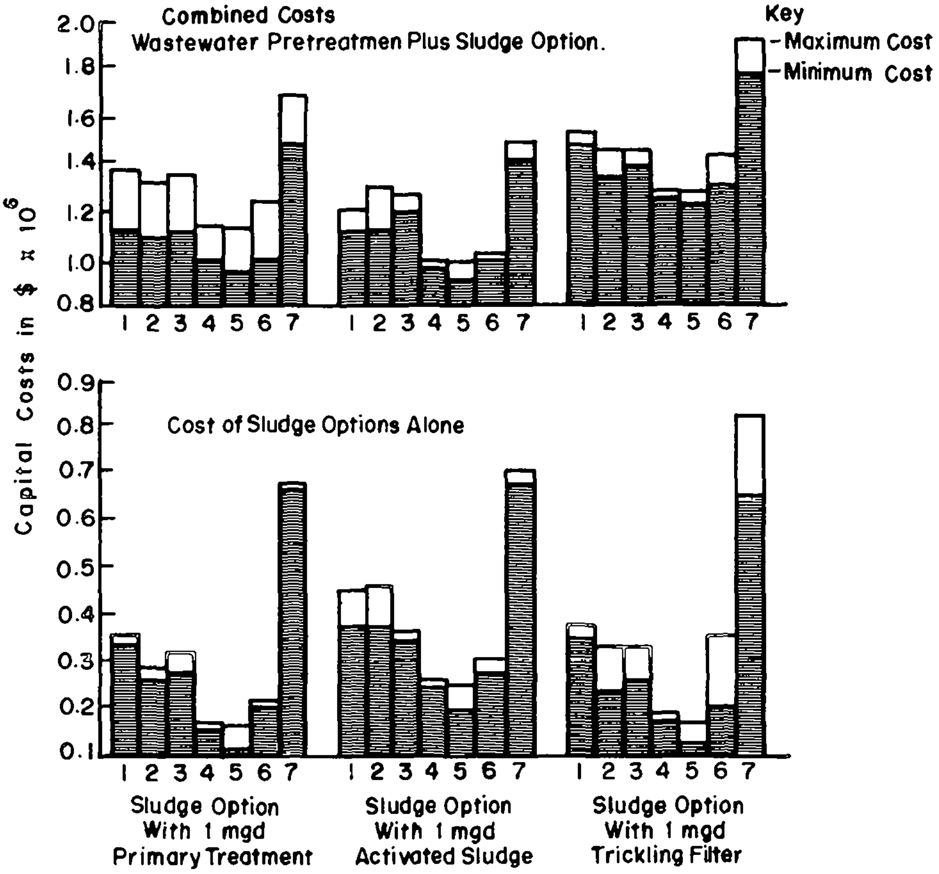
For any project to be successfully implemented, it must be cost effective. This section will deal with some major economic factors which must be taken into consideration for land application of sludges.

YOUNG, et al. (188), in their study on the economic aspects of utilizing municipal sewage wastewaters and sludges on land, have noted that generally society views municipal and industrial sewage sludges as having a negative value in the sense that costs must be incurred to get rid of them. The appeal in sludge land application lies in the recycling of the water and nutrients to produce goods with a positive social value, rather than being dumped into a watercourse. This added value offsets the cost of waste disposal, thus conceivably reducing the net costs of waste disposal.

According to YOUNG, et al. (188), the rational objective, from a social point of view, is to minimize the net cost of waste disposal, both in terms of costs readily measurable, and in terms of costs not so readily measurable. In order to make rational decisions regarding land application as a method of waste treatment, a community needs information on costs of conventional treatment and costs of land utilization. Such a cost evaluation must also include the value of sludges applied to land, indirect costs and benefits, and the incidence of treatment costs (188). For economic evaluation purposes, the net cost of a land application system can be determined by taking the cost of the system, subtracting the benefits derived from the addition of nutrients and from the improved tilth, and subtracting the cost of the most cost-effective non-land application system (72).

Various factors affect the costs of conventional sewage treatment. Some important factors are size of community, degree of treatment, nature of the wastes, type of system, etc. (188). In order to estimate costs with any degree of precision, each potential disposal system must be studied individually. Only data specific to the community or locality should be compared.

A substantial portion of the costs for municipal sewage treatment is attributable to sludge handling and disposal. For example, in the U.S., pretreatment capital costs range roughly from 10% (option 5, trickling filter) to 46% (option 7, activated sludge) for the 1 mgd (3780 cu.m./d) facilities included in Fig. 25. Operating costs represent about the same range (11% for option 5, primary treatment, to 36% for option 1, activated sludge), as shown in Fig. 26. However, in considering these figures, it must be borne in mind that the values are for U.S. and may be outdated. The idea is to present comparative costs between systems rather than the absolute costs of a specific system (4). As mentioned before, costs should be determined specific to the locality. In one study in England, it was estimated that the cost of sludge treatment and



Sludge Options

1. Gravity,Chemical,Vacuum Filtration, Incineration, Landfill
2. Chemical,Centrifuge,Incineration, Landfill
3. Gravity, Porteous, Vacuum Filtration, Incineration, Landfill
4. Gravity, Digestion, Sand Drying, Landfill
5. Gravity, Digestion, Land Spreading
6. Gravity, Digestion, Vacuum Filtration, Landfill
7. Gravity, Digestion, Vacuum Filtration, Ocean Dumping

Figure 25. Comparative Capital Costs for Selected Sludge Options Occurring in Conjunction with Three Waste-Water Pretreatment Regimes (Cited in 4).

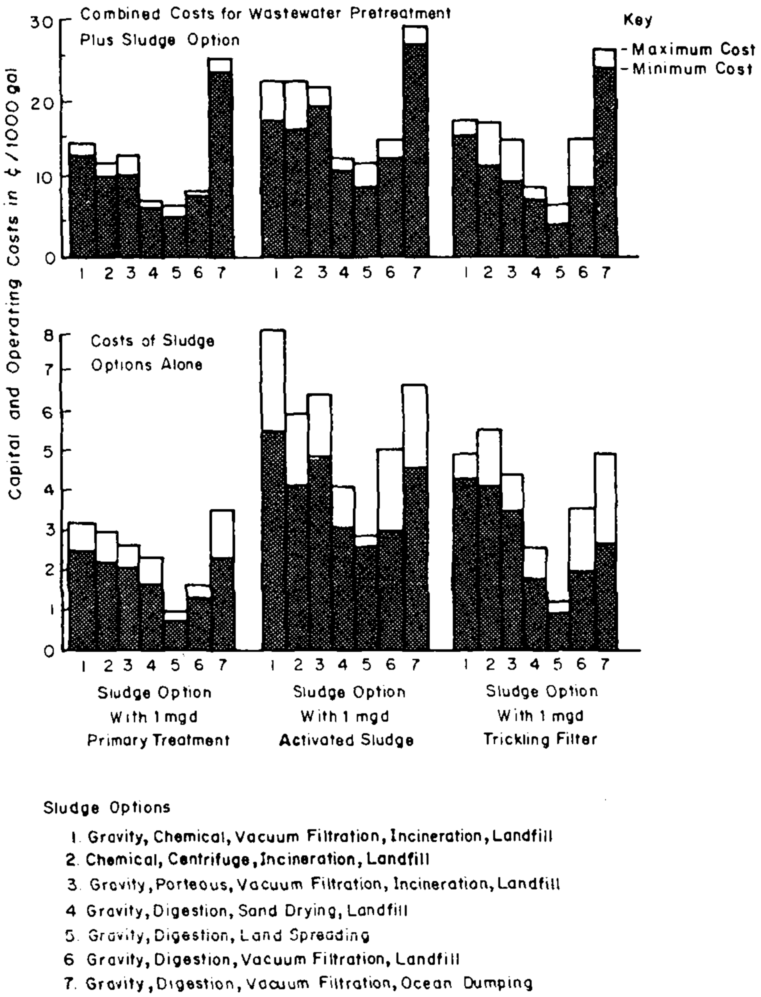


Figure 26. Comparative Operating Costs for Selected Sludge Options Occurring in Conjunction with Three Pretreatment Regimes (Cited in 4).

disposal was 40 percent of the total costs, using biological treatment without tertiary stage (189).

Actual costs generally vary, depending on the type of disposal system, sludge characteristics, population served, land costs, and distance to the ultimate disposal site (188). It is generally accepted that the application of liquid sewage sludge to land is the most economical disposal alternative for smaller cities (10,000 to 100,000 population) when the application site is less than 30 miles (48 km) from the treatment plant. Other alternatives may be more economical if the distance exceeds 30 miles. Another study in the U.S. (190) revealed that land spreading of sludge appears to be a low-cost alternative for communities producing above approximately 350 dry tons (318 dry tonnes) of sludge per year.

In the case of sludge application to land, costs incurred for transporting and applying sewage sludges to land are the major expenses (188). Although dewatering reduces the amount of water that must be hauled along with the sludge solids, the costs for dewatering may be greater than the reduction in transportation costs. Among the transport systems, tank trucks appear to be the most convenient and economical for small quantities of sludge and short hauls (smaller communities) and pipelines more economical for large quantities and longer distances. Similar results have been published in other reports (45).

In an on-site survey of 24 communities with small to medium-sized plants (all with throughput of less than 100 million gallons per day) it was found that (191); (i) land spreading of liquid sludge was far less expensive than sludge dewatered by vacuum filtration, (ii) personnel costs represented the largest single cost item for both liquid and dewatered sludge landspreading, and (iii) liquid sludge was more readily acceptable to the farming community than dewatered sludge.

Cost relationship may be developed for different sludge disposal alternatives in each community for relative comparison and establishment of the most cost-effective method of disposal (194). However, application of sewage sludges to land will usually be competitive with other sludge disposal methods and often will be more economical, especially for smaller communities (188). A literature review by REISNER and CHRISTENSEN (192) suggests that under a rather wide range of conditions, land application is the least expensive method of disposal (and use) of municipal sewage sludge, particularly when we consider the significant benefits is the form of foregone costs of commercial fertilizer associated with land application of sludge. In addition to the direct benefits of sludge land application, there may also be indirect effects like changes in the regional economic activity through increased crop production.

11.2 Market Considerations

Sewage sludge marketing as fertilizer for agricultural production has become a business in many parts of the world (193). This is especially true in these days of energy crises and the skyrocketing prices of commercial fertilizers.

The ability to market sludge depends on factors like closeness to the market, quality of the sludge, etc. (15). The primary markets for sludge are usually nearby farms. Cost-benefit analysis should be conducted to compare the value of the nutrients with the cost of delivery and application for various forms of sludge (eg., liquid, dewatered). The actual price of the sludge should be no greater than that of commercial fertilizers, in terms of unit costs of available nutrients. Improvements in crop yield from sludge application can also be part of the marketing scheme (13).

In addition, to achieve acceptance by farmers, some cost-sharing arrangement between the farmer and the municipality for the purchase of capital equipment may be needed to provide an incentive for the farmer to make the necessary investment. For a succesful land application project, every party affected by the transaction, including the recipient of the sludge, his neighbours and the taxpayers of the sewage treatment district, must be at least well off, financially and otherwise, with land application as without. From an equity standpoint, all parties and the general public should share in the gains, or savings, which may result from land application of sewage sludges (188).

12. PUBLIC ACCEPTANCE AND PARTICIPATION.

Public acceptance is often cited as a key determinant for the success of a land application project. Even if a site has all the appropriate characteristics for sludge application, it may be inappropriate from the standpoint of the community in which it is located. It is costly to go through engineering studies and identify a site for sludge application, and subsequent rejection by the community would make the process even more costly (4).

Gaining community support and involvement in developing a sludge management strategy is both difficult and important. It is difficult because of the combination of ignorance, distaste, and misconceptions regarding sludge. Few people know what sludge is or realize the complexities involved in its management and disposal. As a result, few people show interest in a sludge management program until it becomes an issue because of controversy or apparent cost to the community. Community involvement from the very beginning in selection of a sludge management strategy is important to bring concerns out into the open, to provide adequate discussion of these concerns, and to provide the information needed to make an intelligent reasoned decision (2).

Fear of disease being spread from a land application system is a factor that may prevent the public from accepting a land application system in their community. The public's fear can be allayed by informing them about appropriate processes that are used to protect public health. Fear of toxic elements is another reaction to land treatment. The public must realise that no cases of toxic element poisoning of humans have been associated with land treatment. The public may also fear that land application will create a nuisance by its odor and unsightly appearance. These fears may be quelled through information about modern techniques of good management (4,196).

The community may also resist the idea of land application as a sludge management alternative based on economic grounds (196). The effects of land application on the local economy must be carefully reviewed and discussed with the public to avoid fear based on ignorance. The site for land application must be chosen carefully so as not to interfere with areas of historic or environmental importance (4).

Public advisory boards may be set up composed of representatives from interest groups in the community. Public participation can be organised in two ways: (i) reactive, and (ii) participative. In reactive programs, the major events in the planning process, such as choice of possible sites, are presented to the public. Reactions to the information presented and the remarks of the participants are taken into consideration. The participative approach involves the public at all stages of development of the project, generating useful and informed feedback and public support. The project staff should work to change the public's perception of sewage from viewing it as dirty and objectionable to viewing it as a misplaced resource (4).

An extension service in the form of a public information program will go a long way in ensuring public acceptance by allaying public ignorance of the innumerable benefits of land application of sludge. It might include a newsletter, site visits, public meetings, presentations and discussions including audiovisual aids like radios, TV programs etc. Newspapers, radio, and television are effective means for communicating with the public (4,195). Public information/participation is the lifeline for land application projects. A constructive program must involve open, two-way communications between the public and project proponents. All parties should learn from each other, and emerge reasonably satisfied from this planning effort (195).

13. LEGAL ASPECTS.

Although nightsoil and sewage have been used in 'sewage farms' for crop cultivation in countries like China and India for many years, developing countries have not recognised land application of sludge as an effective waste treatment alternative. Hence, unlike the developed countries, legislations and guidelines for sludge land application have not been developed to any extent in these countries, and hence literature on this aspect is forthcoming.

A review of sludge management legislations in the U.S. (197) gives an idea of the legislations that were instrumental in establishing a sound and environmentally safe sludge disposal strategy in the United States:

In the U.S., most legislations and regulations affecting the quantity and quality of sludge and methods of sludge disposal have been the result of efforts to maintain or improve the quality of the nation's air, water and land resources. In the 1970's Congress enacted pollution control legislation placing a high priority on a clean and healthful environment, such as the Clean Air Act amendments of 1970; Federal Water Pollution Control Act amendments (FWPCA) of 1972; Marine Protection, Research and Sanctuaries Act of 1972; Toxic Substances Control Act (TSCA) of 1976; and the Clean Water Act (CWA) of 1977. All have had a distinct impact on sludge management and disposal.

The Act (FWPCA) of 1972 not only mandated and funded improved wastewater treatment, but also precipitated the generation of increasing quantities of sludge as effluent quality improved. As part of the overall objectives of the Act, discharge of sludge into navigable waters of the nation was specifically prohibited. A similar stand regarding discharge of sludge into the marine environment was expressed in the Marine Protection, Research and Sanctuaries Act, which limited ocean dumping of most materials. Two specific conditions will effectively eliminate the ocean dumping of sludge: mercury in the solid phase (dry basis) of the material is not to be greater than 0.75 ppm, and cadmium is not to be greater than 0.6 ppm. Sludge commonly contains mercury and cadmium concentrations of at least 5 ppm. According to the federal time table, ocean disposal of sludge is scheduled to be phased out by December 31, 1981.

Although no disposal mode results in complete discharge of sludge into the air, incineration of sludge produces emissions that must be held within the air quality requirements specified by the Clean Air Act amendments of 1970. Incomplete combustion of sludge can produce particulates, hydrocarbons, and carbon monoxide. There is also the possibility for discharging of pollutants such as sulfur dioxide, nitrous oxides, and heavy metals such as mercury and cadmium. Consequently, all sludge incineration facilities must use proper emission controls and follow good operating procedures to meet the requirements of the act. One major objective of the Resource Conservation and Recovery Act (RCRA) of 1976 was to establish resource conservation and recovery as the preferred solid waste management approach whenever technically and economically feasible. Clear emphasis was put on protection of public health and the environment in such recycling. A subsection of RCRA titled "Hazardous Waste Regulation" provided for "cradle-to-grave" management of solid waste that may pose a substantial or potential hazard to human health or the environment. Sewage sludge per se is not considered a hazardous waste. However, sludge may contain substances considered hazardous, especially when applied to agricultural land. Cadmium and polychlorinated biphenyls are substances specially identified as toxic and of concern.

In 1979, criteria for the application of sludges to land used for the production of food-chain crops were published by the U.S. Environmental

Protection Agency (Section 3). These criteria were developed to meet the requirements of RCRA and the Clean Water Act..

Substances considered hazardous or toxic have also been addressed in the Toxic Substances Control Act (TSCA). Though as many as 20,000 substances may eventually be placed on the toxic substances list, few are present in most sludges in amounts that would be considered to present a substantial risk to public health or the environment. For example, polychlorinated biphenyls (PCBs) considered a prime target of TSCA, have not been produced in the United States since 1977. In spite of the low biodegradability of PCBs, their concentration in the environment (and in sludge) will continue to decrease. Because the PCB content of most sludges is small, rarely more than a few sentences are devoted to the chemical in guidelines for the land application of sludge. The potential problem of trace quantities of other toxic organic substances in sludge has not been addressed because current information is inadequate to support specific standards or to demonstrate a public health risk. Cadmium is the principle heavy metal considered by many to be sufficiently toxic to human health to limit the application of sludge to agricultural land. Cadmium, however, is not the only metal that must be considered in evaluating the application of sludge to land. Other metals such as zinc, nickel, and copper can also be limiting, because of their toxicity to plant life and animals, if the metal content of a resultant crop is above certain concentrations.

In the Clean Water Act (CWA), Congress recognised and emphasized the potential benefits of sludges as a resource, as well as the potential hazards. Incorporating the concept that sludges are resources out of place, this Act stated that the Environmental Protection Agency is not to make grants for treatment works unless the applicant has fully studied and evaluated innovative and alternative processes of waste management. These alternative processes include the land application of sewage sludge. Combining the recycling approach expressed in RCRA with the cautionary aspects expressed in other laws, the Act (CWA) required guidelines to be prepared for the proper management of the application of sludge onto agricultural land.

To prevent entry of toxic substances into the environment, operators of projects using land application of sludge are required to: (i) analyse the sludge for cadmium or other toxic substances, (ii) ensure that the sludge has been stabilized properly, (iii) examine site-specific characteristics of special concern such as soil type and potential impact on ground water, (iv) determine the appropriate sludge application rates based on site characteristics and the crop management plan, (v) determine what monitoring is required, and (vi) develop any necessary contingency plans. It is the intent of the Congress to maximize the value of sludge as a resource and to minimize enviromental and public health hazards by promoting good management programs.

14. CASE STUDIES.

A number of experimental/operational systems have been designed for land application of sludge in the United States, England and other western countries. Although there is a great potential in the East, it has paid very little attention to this sludge disposal (and reuse) alternative and there are hardly any systems worth mentioning.

In N. America, land application of sludge is being effectively employed in many locations as shown in Table 42. It takes the acceptance by and dedication of many people to place these land utilization systems into operation,

Table 42. Communities Effectively Practicing Land Utilization (12, 207).

Communities	*Flow* *MGD*	*Sludge Utilized dry tons/day*
	LIQUID LANDSPREADING	
Clinton, NJ	1	0.5
Rochester, IN	1	0.8
Little Falls, MN	1	0.6
Peru, IN	2.5	0.8
Bowling Green, OH	3.5	1.7
Muncie, IN	17	10
Salem, OR	30	8
Madison, WI	36	27
Seattle, WA	150	28
Chicago, IL	909	165
	COMPOSTING	
Durham, NH	0.8	0.7
Burlington, VT	5.8	2.3
Toms River, NJ	6.5	7.8
Bangor, ME	7	2
Upper Occoquan, VA	8	13
Windsor, Ontario	21	25
Camden, NJ	32	12
Philadelphia, PA	113	30
Washington, DC	300	55
Los Angeles, CA	440	150
	DEWATERED LANDSPREADING	
Little Falls, MN	1	0.4
Marion, IN	9	0.2
Fort Worth, TX	75	41
Toledo, OH	78	35
Denver, CO	140	125
Washington, DC	300	65
	HEAT DRYING	
Largo, FL	8	2.5
Houston, TX	73	18
Milwaukee, WI	132	190
Chicago, IL	909	131

especially in more densely populated areas. A study of successful systems like those in Chicago (198,216), Denver (199,200), etc., gives an insight into how land application of sludge can be used to solve waste treatment problems effectively and how it can be successfully used to beneficially recycle sludge back to land. In England, 90 million gallons of digested sludge is applied to the land each year at Hertfordshire. The system is named HYDIG (4). Other European countries have also being experimenting with such projects. It will not be long that developing countries will resort to this alternative to dispose of sludge effectively and beneficially, especially since it has a high potential in these countries due to availability of large tracts of agricultural land, increasing costs of commercial fertilizer due to the energy crises, and the increasing concern for water and air pollution.

15. RESEARCH NEEDS.

At present there is insufficient knowledge of both the beneficial and the potentially harmful effects of sewage sludge in agriculture (201), although, new programs, new research results and new concepts in the field are developing daily (202). Some of the important areas of specific research identified in this review are summarized below:

(a) There is little agreement on the allowable sludge application rates. The great variation in the application rates illustrates the difficulty in evaluating the environmental impact of sludge application on to land. Concerted efforts have to be taken to standardize sludge application rates on various types of land.

(b) Although work is already in progress, the agronomic effects of sewage sludge application to land have yet to be clearly defined. Efforts have to be made to establish sludge-plant growth relationships, and sludge loading limitations for different crops, soils, climates, etc., have to be determined.

(c) More is to be learnt about soil-biology implications of sludge land application, since these play an important role in sludge decomposition and transformation in the soil in addition to posing hazards to plant and animal life.

(d) Although the toxic effects of heavy metals are beginning to be understood, there is no general agreement on how to relate trace element contents of sludge and soil to human health hazards.

(e) So far limits for allowable heavy metal concentrations in plants tissues consumed by humans or animals have not been set.

(f) The effects of toxic organic compounds have not been fully ascertained at present. Environmental chemistry-fate models may be developed to evaluate the fate and environmental concentrations of various contaminants upon land disposal.

(g) In evaluating health risks from land treatment, a comparison to those from conventional treatment is necessary. Evaluating health risks is a difficult task and more research is required to evaluate the same.

(h) Another area that deserves more study is pathogen survival in groundwater. Although few studies have been made on bacterial survival in groundwater, it appears that bacteria may persist in underground water for months.

(i) Ova of the intestinal parasitic worms are generally resistant to adverse environmental conditions and are still present in sewage sludges, creating concern with food chain transfer by the sludge-milk-human route. This is a field requiring an immediate, intensive research effort.

(j) An area which needs more research is the survival of pathogens in aerosols. At least some potential health effects are related to the production of aerosols due to the presence of virus and bacteria in them; however these deleterious effects have yet to be fully established.

(k) Although there is no conclusive evidence that insect or rodent transmitted diseases increase in land application sites, more investigation is needed to evaluate this problem.

(l) Evidence that nitrogen in sludge presents either more or less hazard than equivalent amounts of nitrifiable or plant-available N from inorganic sources, is lacking. Research in this area may be very useful.

(m) Technically superior, better integrated and more comprehensive environmental monitoring programs must be developed. Groundwater modeling may be undertaken to forecast the chemical transport of contaminants in the groundwater (203).

(n) Systems modeling, considering land option as one of the possible forms of treatment, should be studied.

Apart from those listed above, there may be other research needs; but it must be emphasized that, whenever feasible, in our research planning, we must make it a habit of taking the broader and more ecological view (92). Only then will our ultimate aim of a better and much cleaner environment be realised.

16. CONCLUSIONS.

In summary it might be said that although sludge application on land has some disadvantages, counterbalancing all these disadvantages is an impressive list of advantages. It minimizes pollution of air or water, can be economical, conserves organic matter and nutrients for beneficial purposes, and can provide a permanent, environmentally sound solution to the disposal of sludges from wastewater treatment plants.

From the experiences of the developed countries, it may be deduced that land application of sludge will also have tremendous possibilities in the developing countries. Scarcity of irrigation water during certain periods is a problem for certain Third World Countries. Land application of liquid sludge can ameliorate this situation to a great extent. Besides, with the escalating energy costs, chemical fertilizers are becoming increasingly expensive and beyond the reach of poor or marginal farmers. Sewage sludge is not only a source of nutrients to crops, but is also a good soil conditioner. Land treatment is the controlled application of sludge under sound guidelines and good management and is not mere dumping for disposal purposes; hence it is also environmentally safe. Therefore concerted efforts should be made by the national and local authorities in developing countries to consider the viability of land application as an alternative for sludge treatment and disposal.

This report summarizes the existing state of knowledge in the field of land application of sewage sludge. It is hoped that such a review would be a source of information to those who are already working in the field and stimulate possible activity in countries or regions not practising land treatment so far.

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