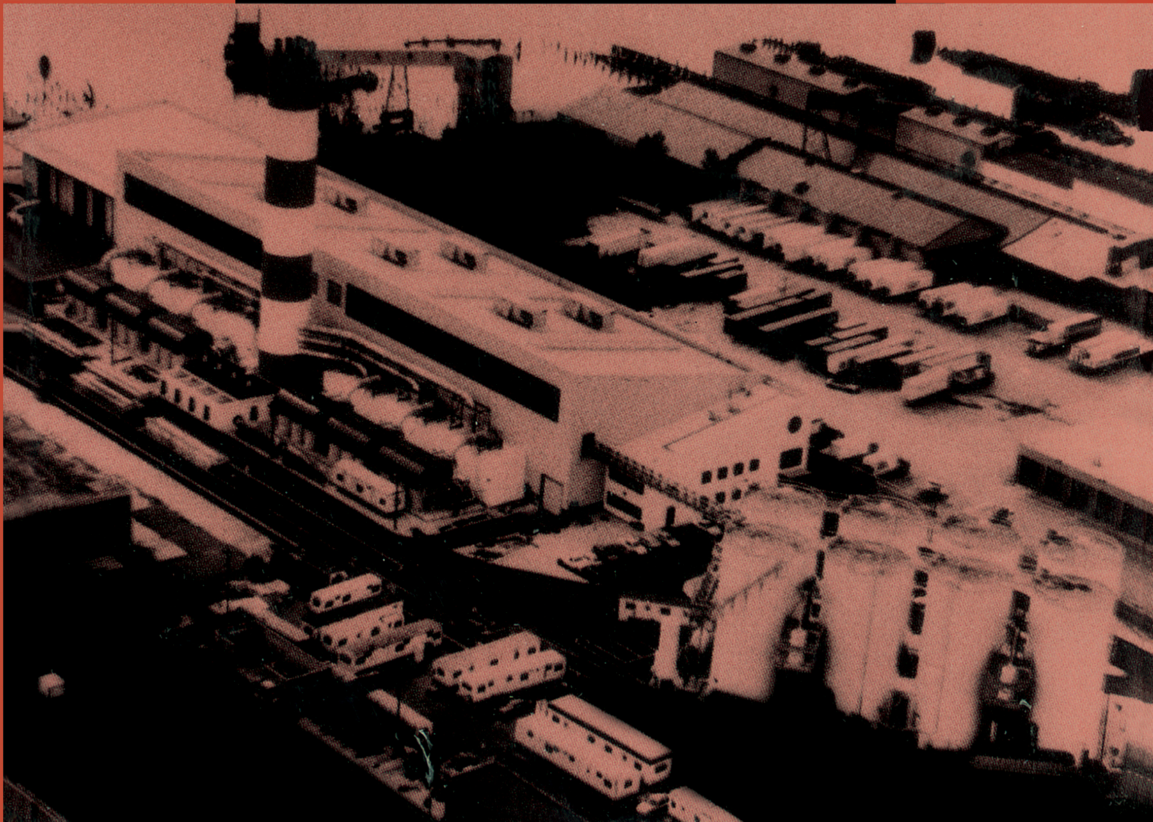
BIOSOLIDS TREATMENT AND MANAGEMENT

Processes for Beneficial Use

edited by **Mark J. Girovich**



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BIOSOLIDS TREATMENT AND MANAGEMENT

Processes for Beneficial Use

edited by

Mark J. Girovich

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Preface

Treated municipal wastewater solids (biosolids) represent a significant and valuable resource which can be recycled for various beneficial uses. The United States Environmental Protection Agency regulations (40 CFR Part 503 "Standards for the Use of Disposal of Sewage Sludge") promulgated on February 19, 1993, have provided new momentum and defined regulatory conditions for implementing beneficial uses of biosolids.

Treatment and management of biosolids is one of the most challenging problems in the wastewater treatment industry. It is complicated by a variety of treatment and end-use options. New federal and state regulations conerning environmental safety and public health have imposed significantly more complex requirements for biosolids treatment, use and disposal. Selecting feasible options that conform to regulations, while minimizing cost, has become very challenging. With ocean disposal no longer allowed, landfills filling up and incineration already expensive and often socially unacceptable, biosolids recycling through beneficial use is gaining in popularity. Such recycling has been practiced by many communities for years in the form of land application of stabilized biosolids. The more advanced treatment options of digestion, composting, heat drying and alkaline stabilization have been developed in recent years to provide marketable products which, because of the additional treatment, are usually subject to fewer regulatory controls.

This book was conceived late in 1993 after the new environmental, safety and public health regulations concerning municipal sludge (biosolids) treatment, management and disposal were introduced. It is written by a group of authors with many years of practice in the field and reflects their unique experience.

The text emphasizes the use of biosolids, reflecting the authors' strong belief that biosolids are a valuable resource and should be beneficially employed in the context of environmental, safety and public health regulations. By providing valuable technical and economic data, this book should prove to be an invaluable resource for municipal administrators, engineers, consultants, students and practitioners in the field who must know how to evaluate and select the best municipal and industrial wastewater solids (biosolids) treatment, management and disposal options. This book contains descriptions of the processing equipment, economics and regulatory and environmental protection issues related to biosolids management and use.

I would like to express my gratitude to all the people who have been helpful in the creation of this book. Special thanks are extended to Sue Gregory, Jamie Kaiser, and Kathleen Wooldridge (Wheelabrator Clean Water Systems Inc., Bio Gro Division) for their assistance in preparing the manuscript.

Mark J. Girovich

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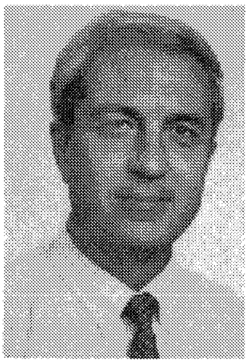

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1

Biosolids Characterization, Treatment and Use: An Overview

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I. BIOSOLIDS GENERATION AND BENEFICIAL USE

Municipal wastewater treatment produces two products: clean water and water slurries which are usually referred to as sludges.

While clean water is disposed of directly into the environment, it is not feasible, environmentally or economically, to do so with the solids generated by wastewater treatment processes. They must be treated prior to disposal or beneficial use to comply with public health, safety, environmental and economic considerations.

Municipal wastewater treatment solids contain significant amounts of organic matter as well as inorganic elements which represent a valuable resource. These components of the solids, after appropriate treatment, can be beneficially used (recycled) as a fertilizer, soil amendment or other beneficial use products. Energy contained in the solids can be recovered. Ash resulting from the solids incineration can also be used beneficially.

Recognizing potential value of wastewater solids, the term *biosolids* is used in this book to mean a product of the wastewater solids treatment that can be beneficially used.

In 1989, 5.4 million dry metric tons of municipal solids were produced per year by approximately 12,750 publicly owned treatment works (POTWs) [1]. Current (1995) municipal solids production is approximately 8.0 million dry metric tons per year and is expected to increase substantially by the year 2000 due to population growth, improvements in POTW operation and stricter treatment standards.

Treatment and disposal of municipal solids in the USA is a growing business estimated at several billion dollars annually. This business, similar to the municipal wastewater treatment industry, is financed by taxation (federal grants, state taxes, sewer fees, etc.)

Quantities and quality of biosolids produced by the POTWs vary widely and depend upon the origin of wastewater, type of treatment and plant operational practices.

Biosolids in the U.S. have been managed as follows (1992, dry metric tons):

TABLE 1-1 DISPOSAL OF MUNICIPAL SOLIDS IN THE USA [1]

Co-disposal in MSW landfills	1,818,700	34.0%
Land application	1,785,300	33.3%
Incineration	864,700	16.1%
Surface disposal	553,700	10.3%
Ocean disposal*	335,500	6.3%
TOTAL	5,357,900	100%

* Ended in June 1992

In the land application category, the following beneficial use options are growing in popularity (design capacity, dry metric tons per year, 1995 estimates):

- Heat Drying and Pelletizing 375,000
- Composting 550,000
- Alkaline Stabilization 650,000

The European Union (EU) (12 countries) generated over 6.5 million dry metric tons of municipal solids in 1992. By the year 2000, the amount will increase up to 9.0 million dmt/year. The EU directives of 1986 and 1991 generally promote beneficial use of sewage sludge solids [2]. The future of beneficial use in the EU will depend on the legislation regarding standards for beneficial use and incineration as well as the acceptance of beneficial use versus incineration by the population. At present, the beneficial use in the EU varies from 10 to 60 percent (Table 1-2).

Japan generates over 1.4 million dmt/year with approximately 60% incinerated. Accurate data on solids disposal in developing countries of Eastern Europe, Asia, Latin America and Africa are not available at present. Detailed discussion on biosolids disposal worldwide is provided in References [2] and [11].

TABLE 1-2 DISPOSAL OF BIOSOLIDS IN EUROPEAN UNION [2][11]

EU Country	Agricultural Use %	Landfill %	Incineration %	Other %	Sea %	Annual Production dmt/year x 1,000
Germany	27	54	14	5	-	2,700
United Kingdom	42	8	14	13	30	1,107
France	60	203	20	-	-	852
Italy	33	55	4	8	-	816
Spain	50	35	5	-	10	350
Netherlands	26	50	3	19	2	323
Denmark	54	20	24	2	-	170
Belgium	29	55	15	1	-	200
Greece	10	90	-	-	-	48
Ireland	12	45	-	8	35	37
Portugal	11	29	-	-	60	25
Luxembourg	12	88	-	-	-	8

The US Environmental Protection Agency (EPA) actively promotes beneficial use of municipal solids because it decreases dependence on chemical fertilizers and provides significant economic advantages. Over 20 years of research have been devoted to the use of biosolids on agriculture and similar beneficial applications. Beneficial use includes:

- application to agricultural and nonagricultural lands alone or as a supplement to chemical fertilizers
- application in silviculture to increase forest productivity

- use in home lawns and gardens
- use on golf courses
- application to reclaim and revegetate disturbed sites such as surface-mined areas
- use as a daily, maintenance and final cover for municipal solid waste (MSW) landfills.

Land application is essentially the placement of appropriately treated biosolids in or on the soil in a manner that utilizes their fertilizing and soil conditioning properties. It includes agricultural, forest and site reclamation applications, and a number of biosolids-derived products, such as digested, dried, chemically or heat treated biosolids, and compost. Biosolids-derived products are distributed in various forms, such as in bulk, packaged, further processed, enriched, sold to public, etc. They are applied to agricultural and nonagricultural lands, soil reclamation and revegetation sites, forests, lawns, gardens, golf courses, parks, and so forth.

Surface disposal includes disposal in monofills and dedicated sites. [Disposal on dedicated sites is a beneficial use method of applying biosolids at greater than agronomic rates at sites specifically set aside for this purpose to restore disturbed soils (e.g., strip mines).]

Incineration is generally regarded as a nonbeneficial disposal method of solids management unless heat recovery for steam and electricity generation is included in the process.

One or more levels of treatment (i.e., primary, secondary and tertiary) are used to clean wastewater. Each level of treatment provides both greater wastewater clean-up and greater amounts of municipal solids.

- Primary solids are removed by gravity settling at the beginning of the wastewater treatment process. They usually contain 3.0 to 7.0 percent total solids (%TS), 60 to 80 percent of which is organic matter (dry basis). The primary solids are generated at the rate of approximately 2,500 to 3,500 liters (660 to 925 gallons) per each million liters of wastewater treated.
- Secondary solids are generated by biological treatment processes called secondary treatment (e.g., activated sludge systems, trickling filters and other attached growth systems which utilize microbes to remove organic substances from wastewater). They usually contain from 0.5 to 2.0%TS. The organic content of the secondary solids ranges from 50 to 60%. About 15,000 to 20,000 liters (3,965 to 5,285 gallons) of these solids are generated per each million liters of wastewater treated.
- Advanced (tertiary) solids are generated by processes such as chemical precipitation and filtration. The solids content varies from 0.2 to 1.5%TS with the organic content of the solids in the 35% to 50% range. About 10,000 liters of solids (2,642 gallons) are generated additionally per each million liters of wastewater treated.

TABLE 1-3 SOLIDS GENERATION [1]

Item	Unit	Primary	Secondary	Advanced
Amount generated	liters	2,500-3,500	15,000-20,000	10,000
Percent total solids	%	3.0-7.0	0.5-2.0	0.2-1.5
Dry biosolids quantity	metric tons per million liters	0.1-0.15	0.2-0.3	0.02-0.15
	tons per million gallons	0.42-0.55	0.8-1.2	0.08-0.6

Table 1-3 provides for quick, approximate estimates of the total biosolids generated as a function of a POTW wastewater influent flow. For example, a 30 million gallon per day POTW (30 mgd) with primary and secondary treatment (typical for a large number of the POTW's in the USA) will generate 30 mgd x (.485 + 1.0) = 44.5 dry tons of biosolids per day (dtd) approximately. (0.485 and 1.0 are average biosolids generation for primary and secondary treatment, tons per million gallons respectively.)

II. BIOSOLIDS CHARACTERIZATION

Characterization of biosolids by their source (primary, secondary, etc.) provides only limited information about their properties. There are numerous other physical, chemical and microbiological parameters which are important for biosolids' treatment and management.

A. Composition and Beneficial Properties

1. *Solids Concentration*

Solids concentrations are measured and expressed either as mg/l (milligrams per liter) or as percent (%) of solids. In all cases in this book it is assumed that: 10,000 mg/l = 1% total solids (TS).

Note that percentage of total solids is weight/weight ratio while solids concentration (mg/l) is weight/volume ratio. The equation above is valid only with the assumption that specific gravity of biosolids is equal to that of water (1.0) which, in many wastewater solids, especially those of industrial origin, is not true. The standard procedure for determining solids concentration employs drying a measured volume of biosolids to a constant weight at 103°-105°C. The solids concentration is the weight of dry solids divided by the volume of the sample expressed in mg/l. In order to determine percent of total solids (%TS) as a weight/weight ratio, the identical procedure is applied with a measured weight of the biosolids sample.

Total volatile solids (%TVS) are determined by igniting the dry solids at 550° ± 50°C in a furnace with excess of oxygen. The residue is referred to as non-volatile or as fixed solids (ash) and the loss of weight on ignition determines total volatile solids. Both %TS and %TVS are widely used in the biosolids treatment and management practices as measures of dry matter (or moisture) and organic (combustible) matter in the biosolids.

Total suspended solids (TSS) refers to the nonfilterable residue retained after filtration of a sample of the liquid biosolids and then dried at 103° - 105°C to remove water. The concentration of TSS is the weight of dry solids divided by the volume of the sample usually expressed in mg/l.

Determination of volatile suspended solids is identical to that of total volatile solids using loss on ignition methods. Total solids are the sum of the dissolved and suspended solids. [3]

Water in biosolids is usually categorized as follows:

- Free water is not attached to the biosolids particles and it can be separated by gravitational settling.
- Floc water is trapped within the flock and can be removed only by mechanical forces, which are usually much greater than gravitational force.
- Capillary water adheres to individual particles and can be also separated by mechanical forces.
- Intracellular and chemically bound water is part of cell material and is biologically and chemically bound to the biosolids' organic and inorganic matter.

Approximate amounts of energy required to remove water from biosolids by various methods are as follows (per cubic meter of water) [4]:

- Gravity (thickening): 10^{-3} KW to achieve 2-6% TS
- Mechanical dewatering: 1-10 KW to achieve 15-30% TS
- Thermal drying: 10^{3} KW to achieve 85-95% TS

In other words, water removal requires approximately one million times more energy to achieve 95% TS than to achieve 2-6% TS in the biosolids.

2. *Chemical Composition*

Chemical composition of municipal solids varies greatly depending upon their origin and methods of treatment.

Biosolids contain organic matter, macro and micronutrients and water important for plant growth. Sixteen (16) elements out of ninety (90) found in plants are known to be essential for plant growth and most of these elements are present in biosolids. The elements are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, iron, boron, manganese, copper, zinc, molybdenum and chlorine. Except for boron, animals require all of these elements and, in addition, sodium, iodine, selenium and cobalt. Some of these elements, however, can be detrimental to human, plant or animal life if they are present above certain limits (e.g., copper, zinc, molybdenum, and chlorine) [6].

Certain metals and synthetic organics have been proven to be detrimental and even toxic to human, animal and plant life at certain levels and, as such, are regulated by respective statutes. Extensive studies conducted in the 1980's by U.S. EPA [7] and subsequent analysis of the potential pollutants' concentration, fate, toxicity and detrimental effects on humans and environment resulted in new federal regulations which limit concentrations of ten "heavy" metals (arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium and zinc) in biosolids applied to land or disposed of by various means. Synthetic organics (organic pollutants) are not regulated at present (1995) unless they are at the levels that make biosolids hazardous and subject of other federal regulations (e.g., RCRA, TOSCA). Major solids characteristics are provided in Table 1-4 [5].

Nutrients present in biosolids are absorbed by plants as water soluble ions, mostly through the roots. Dissolved mineral matter in biosolids (and in soil) is present as cations (H^+, Ca^{2+}, Mg^{2+}, K^+, Na^+ and low levels of Fe^{2+}, Mn^{2+}, Cu^{2+}, Al^{3+}, Zn^{2+}) and anions (HCO_3^-, CO_3^{2-}, HSO_4^-, SO_4^{2-}, Cl^-, F^-, HPO_4^-, $H_2PO_4^-$). Table 1-5 illustrates the nutrients' ionic forms generally present in biosolids and available for plants.

Note that carbon is absorbed by plants mostly through leaves as CO_2; hydrogen from water as H^+, HOH, and oxygen through leaves as O_2, OH^- and CO_2.

3. *Macronutrients*

The elements generally recognized as essential macronutrients for plants are carbon, hydrogen, nitrogen, phosphorus, potassium, calcium, magnesium and sulfur. Nitrogen, phosphorus and potassium are the most likely to be lacking and are commonly added to soil as fertilizers.

Although biosolids contain relatively low levels of macro and micronutrients when applied to soil at recommended rates they can supply all the needed nitrogen, phosphorus as well as calcium, magnesium and many of the essential micronutrients.

Nitrogen, phosphorus and potassium (usually referred to as N-P-K) play significant roles in biosolids beneficial use.

TABLE 1-4 MUNICIPAL SOLIDS CHARACTERISTICS [5]

#	Item	Primary	Secondary
1	Total dry solids (TS), %	3.0 - 7.0	0.5 - 2.0
2	Volatile solids (% of TS)	60 - 80	50 - 60
3	Nitrogen (N, % of TS)	1.5 - 4.0	2.4 - 5.0
4	Phosphorus (P_2O_5, % of TS)	0.8 - 2.8	0.5 - 0.7
5	Potash (K_2O, % of TS)	0 - 1.0	0.5 - 0.7
6	Energy content (BTU/lb, dry basis)	10,000 - 12,500	8,000 - 10,000
7	pH	5.0 - 8.0	6.5 - 8.0
8	Alkalinity (mg/L as $CaCO_3$)	500 - 1,500	580 - 1,100
9	Metal Concentrations (mg/kg, dry basis)	Range	Median
	a. Arsenic	1.1 - 230	10
	b. Cadmium	1- 3,410	10
	c. Chromium	10 - 99,000	500
	d. Copper	84 - 17.000	800
	e. Lead	13 - 26,000	500
	f. Mercury	0.6 - 56	6
	g. Molybdenum	0.1 - 214	4
	h. Nickel	2 - 5,300	80
	i. Selenium	1.7 - 17.2	5
	j. Zinc	101 - 49,000	1,700
	k. Iron	1,000 - 154,000	17,000
	l. Cobalt	11.3 - 2,490	30
	m. Tin	2.6 - 329	14
	n. Manganese	32 - 9,870	260

Nitrogen (N) is the most critical part in the plant growth. Poor plant yields are most often due to a deficiency of nitrogen. It is a constituent of plant proteins, chlorophyll and other plant substances. Biosolids nitrogen exists as organic and inorganic compounds. Organic nitrogen is usually the predominant form of nitrogen in soils (90 percent) and in biosolids and it is not available to plants. It must be bacterially converted to ammonium (NH_4^+) and eventually oxidized to nitrate (NO_3^-) to become biologically available.

TABLE 1-5 BIOSOLIDS NUTRIENTS AND THEIR IONIC FORMS [6],[9]

Element	Symbol	Ion or Molecule
Nitrogen	N	NO_3^-, NH_4^+ (ammonium, nitrate)
Potassium	K	K^+
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-} (phosphates)
Sulfur	S	SO_4^- (sulfate)
Calcium	Ca	Ca^{2+}
Iron	Fe	Fe^{2+}, Fe^{3+} (ferrous, ferric)
Magnesium	Mg	Mg^{2+}
Manganese	Mn	Mn^{2+}
Copper	Cu	Cu^{2+}
Zinc	Zn	Zn^{2+}
Molybdenum	Mo	MoO_4^- (molybdate)
Boron	B	H_3BO_3, $H_2BO_3^-$, $B(OH)_4^-$

Nitrogen is a unique plant nutrient because, unlike the other elements, plants can absorb it in either cation (NH_4^+) or anion (NO_3^-) form. Nitrogen forms not absorbed by plants volatilize or oxidize and are lost to atmosphere as N_2 or N_2O. Volatilization of ammonium ion depends upon pH. The higher the pH, the more nitrogen is released as gaseous ammonia(NH_3).

The nitrogen requirements of different plants range from 50 to 350 kg per hectare (45-312 pounds per acre). [1] Heavy application of nitrogen-containing biosolids or chemical fertilizer may result in unused nitrate migrating into surface or underground water with adverse health and environmental effects.

The nitrogen content of primary biosolids is in the range of 2% - 4%; in secondary and anaerobically digested biosolids it is in the 2% - 6% range (dry basis) [7].

Nitrogen in biosolids is usually determined as organic nitrogen (Org-N), soluble ammonia nitrogen (NH_3-N), soluble nitrate-nitrogen (NO_3 -N) and total (Kjeldahl) nitrogen (TKN).

Numerous studies have been conducted on the rate of organic nitrogen conversion into the biologically available forms (NH_4^+, NO_3^-), called mineralization. One method of determining nitrogen mineralization and availability is based on assumption that 15% of organic nitrogen becomes available to plants during the first year and 6% of the remaining, or residual organic nitrogen, is released during the second, 4% during the third, and 2% during the fourth growing season after application. Based on these assumptions, the available nitrogen per ton of dry biosolids and application rate can be calculated [8]. Nitrogen is usually the limiting factor in biosolids land application, unless they have been stabilized by an alkaline material (lime) or contain excessive amounts of heavy metals. In this case, calcium or heavy metal(s) becomes the limiting component. A detailed nitrogen discussion is provided in Chapter 8.

Nitrogen is available from chemical fertilizer in a relatively concentrated form, typically 8 to 40 percent. The chemical fertilizer's nitrogen is valued, however, at $2 to $4 per percent point while the same for organic nitrogen in biosolids is $12 to $17 per percent (1994).

Phosphorus (P) is the second most critical plant nutrient. The nucleus of each plant cell contains phosphorus. Cell division and growth are dependent upon adequate supply of phosphorus. The most common forms of phosphorus are organic phosphorus and various forms of orthophosphates ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) and polyphosphates, such as $Na_3(PO_3)_6$, $Na_5P_3O_{10}$, $Na_4P_2O_7$. Phosphorus is not readily available in most unfertilized soils and is derived primarily from phosphates released by organic matter decomposition. Organic phosphorus is decomposed by bacterial action into orthophosphate PO_4^-. Polyphosphates also decompose (hydrolyze) in water into orthophosphates. Significant portion of phosphorus compounds are water soluble. Stable orthophosphate (PO_4) is predominate form which is absorbed by plants.

Primary wastewater solids contain relatively small amounts of phosphorus. Secondary biosolids contain greater amounts of phosphorus which is generally removed from wastewater by biological means.

Amounts of phosphorus in biosolids depends on phosphorus concentration in the influent and type of phosphorus removal used by wastewater treatment plants. Conventional primary and waste activated processes remove only 20-30% of an influent phosphorus and, therefore, biosolids resulting from these processes contain a small amount of phosphorus (0.1 to 2%).

This amount is sufficient for plant growth when biosolids are applied at the nitrogen requirement rate. Excessive amounts of phosphorus can eventually be built up in the soil and result in leaching.

The phosphorus requirements of different plants range from 0 to 95 kilograms per hectare (0 to 85 pounds per acre). Phosphorus is not removed from wastewater by aerobic or anaerobic digestion. Only chemical precipitation using aluminum and iron coagulants or lime is effective in phosphorus removal. Biosolids resulting from these processes may contain greater amounts of phosphorus.

The following reactions convert phosphorus from wastewater into the forms found in biosolids.

1. Chemical coagulation by alum, $Al_2(SO_4)_3$, and ferric chloride, $FeCl_3$, respectively:
   $Al_2(SO_4)_3\ 14.3\ H_2O + 2\ PO_4^{3-} = 2\ AlPO_4 + 3\ SO_4^{2-} + 14.3\ H_2O$
   $FeCl_3 + PO_4^{3-} = FePO_4 + 3\ Cl^-$
2. Phosphorus removal by addition of slaked lime:
   $Ca(HCO_3)_2 + Ca(OH)_2 = 2\ CaCO_3 + 2\ H_2O$ (removal of water hardness)
   $5\ Ca^{2+} + 4\ OH^- + 3\ HPO_4^{2-} = Ca_5\ (OH)(PO_4)_3 + 3\ H_2O$
   Calcium ion in the second reaction forms precipitates containing orthophosphate.

Potassium (K) is needed by plants for various functions, including maintaining cell permeability, increasing resistance of plants to certain diseases, and aiding in translocation of carbohydrates. Potassium in most soils is found in more than sufficient amounts, however, it is not bioavailable. As a result, use of potassium fertilizers is required. About 150 pounds per acre of potassium is needed for plant growth. Biosolids usually contain small amount of potassium (0.02 to 2.5% dry basis).

4. *Other Inorganic Nutrients*

Calcium (Ca) is rarely deficient in plants. It is needed for cell division, it makes cells more selective in their absorption and it is a constituent of a cell wall. Most soils (except sandy and strongly acid ones) contain sufficient calcium supply. Calcium is supplied to the plants by soluble calcium ions from calcium containing minerals such as $CaCO_3$. Addition of CaO, $Ca(OH)_2$ or $CaCO_3$ to soils is done to correct the pH of strongly acid soils to improve nutrient availability rather than to supply calcium for plant growth.

Biosolids contain calcium in small amounts unless they are the result of processes where lime is used (e.g., lime stabilization).

Magnesium (Mg) is important in chlorophyll formation. There is one atom of magnesium in each chlorophyll molecule. There would be no green plants without magnesium. Most of the plant magnesium, however, is found in plant sap and the cytoplasm of cells.

Magnesium is taken up by the plant roots as cation Mg^{2+}. Magnesium bioavailability is affected by other ions such as potassium, calcium and nitrogen. Magnesium requirements of different plants range from 9 to 36 pounds per acre. Biosolids usually contain small amounts of magnesium (0.3% - 2%, dry basis).

Sulfur ranks in importance with nitrogen and phosphorus as an essential nutrient in the formation of plant proteins; it is also required for the synthesis of certain vitamins in plants. Sulfur-containing organic compounds are present in biosolids and bioavailable sulfate (SO_4^{-2}) is produced as a result of microbial decomposition.

Sulfur requirements of different plants range from 10 to 40 pounds per acre. Biosolids contain from 0.6% to 1.5% of sulfur (dry basis).

5. *Organic Matter*

Organic matter, dead or alive, is largely carbon (approximately 58% by weight), with lesser amounts of hydrogen, oxygen and other elements such as nitrogen, sulfur and phosphorus.

Organic matter in biosolids contains proteins, carbohydrates, fats--compounds composed of long chains of molecules with molecular weights ranging from several hundred to several million.

Organic matter is a nutrient source for plants and microorganisms; in soils it improves water infiltration, aeration and aggregation of soil particles.

Microorganisms (bacteria, protozoa, fungi, and others) decompose biosolids' organic matter and use some decomposition products (carbon, nitrogen and other elements) for reproduction and, as a result, change the biosolids organic matter and release certain products of decomposition (e.g., carbon dioxide, methane, volatile organics including odor pollutants, ammonia, nitrogen, water) into the environment. Bacteria, actinomycetes and fungi are the most active decomposers of organic matter, but some algae, protozoa, rotifers, nematodes and others participate in organic matter decomposition. These organisms also interact in a complex manner at various stages of wastewater and biosolids treatment processes.

Most soils contain relatively small amount of organic matter (1-5% in the top 10 inches of soil) but it largely determines soil productivity.

The biosolids organic matter can have a profound effect on the soil physical properties such as soil fertility, humus formation, bulk density, aggregation, porosity, and water retention. A decrease in bulk density, for example, provides for a better environment for plant root growth. The high organic carbon content of biosolids provides an immediate energy source for soil microbes. The nitrogen in biosolids is in a slowly available organic form which provides for a reliable nitrogen supply. Increased aggregation results in better tilth and less potential for erosion and reduction of runoff. Water retention and increased hydraulic conductivity provide necessary water for plants, especially during drought.

Biologically active organic components of biosolids include polysaccharides, such as cellulose, fats, resins, organic nitrogen, sulfur and phosphorus compounds, etc.; they contribute to the formation of soil humus, a water-insoluble material that biodegrades very slowly and is the product of bacterial decomposition of plant material.

6. *Micronutrients*

Micronutrients such as iron, zinc, copper, manganese, boron, molybdenum (for N-fixation), sodium, vanadium, and chlorine, are needed by plants in small quantities but they are quite important as catalysts in numerous biological processes. The role of chlorine, except for its part in root growth, is not well known. Excessive quantities of some of the micronutrients can render biosolids hazardous to human health, plant and animal life.

Soil and biosolids pH influences micronutrient availability. All metals except molybdenum are more bioavailable at low pH (acidic environment). In near neutral and alkaline environments, metals form insoluble oxides or hydroxides and become nonbioavailable. Also, toxicity caused by excess level of micronutrients may occur. A detailed discussion concerning micronutrients is provided in Chapter 8.

7. *Pollutants*

Biosolids usually contain organic and inorganic components which can adversely affect plant and animal life as well as human health if present at excessive levels. Inorganic pollutants include ten "heavy" or trace metals presently regulated by the U.S. EPA: arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium and zinc. Ranges and median concentrations of heavy metals in biosolids are provided in Table 1-4.

Arsenic, a toxic metalloid, has been the chemical villain of more than a few murder plots. The combustion of coal introduces large quantities of arsenic into the environment. Some formerly used pesticides contain highly toxic arsenic compounds as well as some mine tailings. The U.S. EPA has classified arsenic as a human carcinogen. Arsenic content in biosolids varies widely (Table 1-4).

Cadmium comes from metal plating and mining wastes. Cadmium is chemically similar to zinc (both are divalent cations) and replaces zinc causing acute cadmium poisoning (kidney damage, high blood pressure and destruction of red blood cells). According to the U.S. EPA, cadmium is a probable human carcinogen. Cadmium content in biosolids varies from few to over 3,500 mg/kg, dry basis.

Chromium comes from metal plating and mine tailing. It is an essential trace element. Hexavalent chromium is classified by the U.S. EPA as a human carcinogen.

Copper comes from industrial discharges, mining and mineral leaching; it is an essential trace element, not very toxic to animals, toxic to plants and algae at moderate levels. Copper is not classified as a carcinogen.

Lead comes from a number of industrial and mining sources, leaded gasoline, plumbing, lead bearing minerals, etc. It causes kidney, reproductive system, liver, brain and central nervous system disfunctions. Lead is classified by the U.S. EPA as a probable human carcinogen.

Mercury generates the most concern of the heavy metal pollutants. It comes from minerals, coal combustion, pesticides and fungicides, batteries, and pharmaceutical products. Toxicological effects include neurological damage, birth defects, depression, etc. Mercury tends to accumulate in seafood due to formation of soluble organic mercury compounds. The U.S. EPA has not classified the carcinogenicity of mercury because of inadequate evidence.

Molybdenum comes from natural sources and industrial discharges; possibly toxic to animals, essential for plants. The U.S. EPA has not classified the carcinogenicity of molybdenum because of inadequate evidence.

Nickel sources are minerals and industrial discharges. Nickel deficiency has not been demonstrated to be essential for the proper growth and development of plants or animals. However, excessive levels of this element produce toxic effects in plants, animals and humans. The U.S. EPA has classified nickel as a probable human carcinogen.

Selenium sources are minerals, coal and industrial discharges. It is essential at low levels; toxic at higher levels. The U.S. EPA has not classified the carcinogenicity of selenium because of inadequate evidence.

Zinc comes from industrial waste, metal plating and plumbing. It is an essential element in many metalloenzymes and aids wound healing; it is toxic to plants at higher levels. Zinc occurs in biosolids in relatively large quantities and could limit land application. Zinc requirements vary considerably from crop to crop (e.g., alfalfa requirements are 0.5 pounds per acre, approximately).

Organic pollutants, among others, include hazardous organic substances regulated under RCRA or TOSCA standards.

More detailed study of biosolids pollutants can be found in [9], [10], [11], [13], and [14].

B. Microbiology of Biosolids

Biosolids contain diverse life forms. These microscopic living organisms have both beneficial and detrimental roles in the biosolids treatment and use practices.

Microorganisms in biosolids can be categorized into bacteria, including actinomycetes, viruses, helminths (parasitic worms), protozoa, rotifers and fungi. A limited number of these organisms are pathogenic (i.e., they may cause various human and animal diseases). One of the major objectives of biosolids treatment is pathogen elimination or reduction to acceptable levels. Current regulations do not address protozoa, rotifers and fungi as organisms subject to pathogen requirements because of the lack of analytical methods and because EPA concluded that these organisms are unlikely to survive wastewater and biosolids treatment processes and, thus, should not cause an adverse effect in biosolids use [1].

Bacteria are the smallest living organisms. Most bacteria reproduce by division into two identical cells. Bacteria are very difficult to classify. They are composed of water (80%) and dry matter (20%), about 90% of which is organic. Bacterial dry matter contains carbon (48%), nitrogen (7-12%), phosphorus (1.0-3.0%), potassium (1.0 - 4.5%), sulfur (0.2-1.0%) and trace elements, such as magnesium, sodium, calcium, iron, copper, manganese, and molybdenum. Bacterial organic matter contains proteins (50-60%), carbohydrates (6-15%), lipids and organic acids [12].

Actinomycetes are a large group of organisms which look like elongated cells or filaments. Some actinomycetes have characteristics common to fungi. Actinomycetes are common in biosolids and soils. They are saprophytes and decompose a wide range of organic compounds such as difficult to decompose long chain hydrocarbons, complex aromatic compounds, pesticides and dead microbial biomass. They also decompose readily degradable compounds such as amino acids, sugars and organic acids. They usually grow more slowly than most other bacteria. Some actinomycetes are aerobes, some are anaerobes, and they thrive at a pH of 6.0 to 8.5. Actinomycetes are often found in activated biosolids and scum developed over the aeration tanks and secondary clarifiers. The most frequently reported genera in activated sludge processes are Arthrobacter, Corynebacterium, Mycobacterium, Nocardia and Rhodococcus [12].

Coliform bacteria, especially fecal coliforms,are natural, normally harmless microscopic inhabitants of the intestines of all warm-blooded animals including humans. Coliform bacteria coexist in fecal material with pathogenic or disease-causing organisms such as certain bacteria, viruses and protozoa. Coliform bacteria are also found in soil and on vegetable matter. They are highly concentrated in wastewater and biosolids and generally sparse or not present in other habitats. The presence of coliform bacteria in biosolids and water is considered an indication of contamination. Typical average coliform bacteria populations in biosolids and other materials are (organisms per gram, dry weight) [11]:

- Unstabilized biosolids: 1,000,000,000
- Aerobically digested biosolids: 30,000-6,000,000
- Human feces: 50,000,000,000
- Disinfected effluent: 100
- Wastewater: 8,000,000

One of the coliform bacteria, *Escherichia coli (E. coli)*, is a natural inhabitant only in the intestines of warm-blooded animals and, therefore, its presence indicates fecal contamination and possible presence of pathogens. Fecal coliforms are the principal indicator organisms (along with *Salmonella sp.* bacteria) for evaluating the microbiological contamination of biosolids.

Fecal streptococci include the enterococcus group and several species associated with nonhuman warm-blooded animal wastes. Enterococci are enteric bacteria from humans and their presence indicates contamination of human origin. Fecal coliform to fecal streptococcus ratio can help identify sources of contamination. Ratios greater than 4.4 indicate fecal pollution of human origin; ratios less than 0.7 indicate fecal pollution from nonhuman sources.

Salmonella sp. routinely found in unstabilized biosolids, compost handling facilities and landfills cause various diseases such as acute gastroenteritis (food poisoning), typhoid fever, and salmonellosis.

While indicators are very useful in assessing microbiological contamination, no indicator species is perfect. Coliforms, for example, die off very quickly in water (half life is about 15 hours and only few coliforms survive more than 3 days); however, coliforms may live significantly longer in biosolids.

Viruses are acellular particles which carry genetic reproductive information but are incapable of living outside a host cell. They are extremely small (0.01-0.25 micrometer or micron, μm) and extremely host-cell specific. More than 100 different viruses may be present in untreated biosolids. The major concerns with viruses are their potential for disease transmission and conditions necessary for their destruction in biosolids. Diseases associated with specific pathogenic bacteria and viruses and are summarized in Table 1-6.

Protozoa ("first animals") are very small (5 to 1000 μm in size), single celled animals comprising a diverse group. Protozoa need water; they are present in all aerobic wastewater treatment plants. Their role is important in the activated solids processes (up to 50,000 organisms/mL or about 5% of the dry weight of suspended solids in the mixed liquor); they are present in trickling filters; rotating biological contactors (RBC); oxidation ponds, and natural and manmade wetlands.

Protozoa are parasitic (live on or in other life forms) or free living. Many are parasites of animals. Protozoa are of four different nutritional types: autotrophs (plant-like forms capable of absorbing sunlight and using carbon dioxide to produce organic compounds); saprobic organisms (animal-like forms that do not contain chlorophyll nor require light but rely on the organic soluble compounds); phagotrophs (forms that feed on bacteria); and carnivorous protozoa which feed on other protozoa.

Some protozoa require oxygen and some do not use it and are often unable to grow in its presence.

Optimum pH for protozoa survival is in the 6.0 to 8.0 range. At pH below 5.0 and higher than 8.0 their population is adversely affected. Light is important for autotrophs. Many protozoa compete with one another for bacteria as a food supply, while others compete with bacteria and other saprobic protozoa for soluble organics.

Protozoa play a significant role in bacterial removal from wastewater including pathogenic bacteria that cause diseases such as diphtheria, cholera, typhus and streptococcal infections, as well as removal of fecal bacteria such as *Escherichia coli.* Protozoa are helpful in flocculating suspended particulate matter and bacteria thus aiding both clarification of the effluent and formation of biosolids.

Such protozoa as *Entamoeba histolytica* and *Giardia lamblia* are common in biosolids, especially in warm climates. Their cysts are quite resistant to disinfection.

Rotifers ("wheel bearers") are the simplest and smallest of the macroinvertebrates found in wastewater and biosolids. They are free swimming organisms and range in size from 40 to 500 um (microns) and have an average life span of 6 to 45 days. Rotifers perform many beneficial roles in stabilizing the organic wastes of lagoons and fixed-film and activated biosolids processes. In lagoons rotifers feed on phytoplankton or algae. In the activated sludge process, rotifers consume large quantities of bacteria and enhance floc formation. Generally in aerobic processes the rotifers' large consumption of bacteria and solids contributes to BOD reduction.

Helminths (parasitic intestinal worms and flukes) and Nematodes (roundworms) are free living, microscopic (0.5-3.0 millimeters long and 0.02 to 0.05 mm wide) and macroscopic organisms (*Ascaris lumbricoides* (roundworm), sometimes reaching 20-40 cm in the intestine) which include various worms such as hookworms, pinworms, whipworms, eelworms, roundworms, and many others. They are present in aerobic processes with abundance of oxygen and microbial food (e.g., trickling filters, activated sludge processes). Some nematodes survive temperatures as high as 117 °F (47 °C) and are most active at pH between 3.5 and 9.0.

Ascaris lumbricoides are a serious potential danger to humans from biosolids. Most helminths and nematode eggs and cysts tend to accumulate in primary biosolids. Table 1-6 lists major pathogenic helminths and nematodes and potential diseases.

Fungi. Over 80,000 fungal species have been identified, most of which decompose organic matter. They can be broadly categorized as yeasts or molds. Fungi consist of tubular, filamentous branches 10 to 50 um in diameter. They reproduce by forming spores which are quite hardy. About 50 fungal species can cause human infections affecting primarily lungs, skin, hair and nails.

Fungi are less dependent on moisture than bacteria and can grow on dry biosolids absorbing moisture from atmosphere. They can withstand broad range of pH and temperature. Fungi are important industrial microbes. Yeasts are used in production of alcohols and to synthesize antibiotics, organic acids and enzymes.

Most wastewater treatment processes remove pathogens from the wastewater and transfer them into biosolids. While wastewater is being cleaned, biosolids that are generated by the treatment processes contain a number of pathogenic organisms. Primary biosolids have large numbers of alive and dead protozoa cysts and helminth and nematode eggs. Secondary biosolids contain significant numbers of bacteria and viruses. For example, *Salmonella* are removed at 90% to 99% efficiencies from the water and end up in the biosolids.

The application of untreated biosolids to agricultural lands has the potential of spreading microbial and viral contamination to food crops, surface and groundwater. Wastewater treatment plants, biosolids treatment and handling facilities, compost operations, biosolids landfills and biosolids land application operations if handled improperly are considered potential sources of air- and product-borne pathogens. Proper treatment of biosolids prior to their beneficial use or disposal is of utmost importance in preventing diseases from pathogenic organisms.

TABLE 1-6 PATHOGENIC ORGANISMS AND POTENTIAL DISEASES [12], [16]

Organism	Disease	Mode of Transmission Comments
I. Bacteria and Actinomycetes		
1.1 *Coliform* species	Internal infections, gastroenteritis, diarrhea	Contaminated food and water
1.2 *Vibrio cholera*	Cholera	Contaminated water, food
1.3 *Salmonella* species	Salmonellosis	Food, water Common in biosolids
1.4 *Salmonella* typhi	Typhoid fever	Water Found in biosolids
1.5 *Shigella*	Shigellosis (bacillary dysentery)	Polluted water
1.6 *Bacillus Anthracis*	Anthrax	Disease of animals, rare in humans
1.7 *Brucella*	Brucellosis	Infected milk or meat Found in biosolids
1.8 *Mycyobacterium* tuberculosis	Tuberculosis	Found in biosolids
1.9 *Leptospira interohaemorrhagiae*	Leptospirosis	Contaminated food and drink Found in biosolids
1.10 *Yersinia entercolitica*	Gastroenteritis	Contaminated food and drink
1.11 *Esherichia coli* (usually nonpathogenic)	Gastroenteritis	Contaminated water and food Common in biosolids
1.12 *Clostridium tetani*	Tetanus	Wound contact Found in biosolids
1.13 *Nocardia spp.*	Lung disease (nocardiosis)	Inhalation and contact with skin Found in biosolids

TABLE 1-6 (CONT.)

Organism	Disease	Mode of Transmission Comments
1.14 *Actinomycetes israelii*	Actinomycosis (meningitis, endocarditis, genital infections)	Inhalation and contact with skin Found in biosolids
1.15 *Camphlobacter spp.*	Acute enteritis	Contaminated food and drink Found in biosolids
II. Enteric Viruses		
2.1 Polio virus	Poliomyelitis	Found in biosolids Polio vaccine eliminates disease
2.2 Virus	Hepatitis A	Found in biosolids
2.3 Coxsackievirus, echovirus	Mild infections, meningitis, diarrhea in infants, heart disease, conjunctivitis	Inhalation, water Found in biosolids
2.4 Adenovirus, reovirus	Respiratory infections, influenza, colds, bronchitis, diarrhea	Inhalation, water Found in biosolids
2.5 Rotavirus, calicivirus	Viral gastroenteritis	Inhalation, water
III. Protozoa		
3.1 *Entamoeba histolitica*	Amoebic dysentery	In untreated biosolids used as a fertilizer, resistant to disinfection
3.2 *Giardia lamblia*	Giardiosis	Cysts are not destroyed by disinfection; found in biosolids
3.3 *Criptosporidium*	Gastroenteritis	Found in biosolids
3.4 *Balantidium coli*	Dysentery	Found in biosolids
3.5 *Isospora belli*	Isosporosis	Digestion of viable cysts
IV. Helminths & Nematodes		
4.1 *Ascaris lumbricoides; ascaris suum*	Ascariasis (large intestinal roundworm) Abdominal pain, digestive disturbances, fever, chest pain	Ingestion of eggs in food or drink Found in biosolids wet and dry; most common of helminth

TABLE 1-6 (CONT.)

Organism	Disease	Mode of Transmission Comments
4.2 *Ancylostoma duodenale, Necator americanus*	Hookworm Abdominal pain and digestive disturbances	Ingestion of eggs Found in biosolids
4.3 *Enterobius vermicularis*	Pinworm (enterobiasis)	Ingestion of eggs Easily curable with drugs
4.4 *Trichuris trichiura*	Whipworm (trichuriasis) Abdominal pain, diarrhea	Ingestion of eggs Easily curable with drugs Found in biosolids
4.5 *Taenia saginato*	Abdominal pain, disturbances	Found in biosolids
4.6 Cat, dog, beef, pork worms	Worm infections in humans	Ingestion of eggs
4.7 Various trematodes (flukes)	Intestinal, lung and liver flukes	Ingestion of eggs Found in biosolids
V. Fungi		
5.1 *Aspergillus fumigatus*	Aspergillosis, lung infection	Inhalation of spores Found in biosolids and compost, most common and serious of fungal infections
5.2 *Candida albicans*	Candidiasis (infection of lungs, skin, intestinal tract)	Inhalation of spores
5.3 *Coccidioides immitis* and *Histo-plasma capsulatum*	Lung infection	Inhalation of spores Fungus grows on biosolids in warm and moist conditions
5.4 *Blastomyces dermatitides*	Blastomycosis (lung infection)	Inhalation of spores
5.5 *Cryptococcus neoformans*	Cryptococcosis (lung infection)	Inhalation of spores
5.6 *Sporothrix schenkii*	Sporotrichosis	Broken skin contact

When biosolids are applied to land, humans and animals can be exposed to pathogens directly by coming into contact or indirectly by consuming water or food contaminated by pathogens. Insects, birds, rodents and people involved in biosolids processing can also contribute to the exposure.

Some pathogenic organisms have limited survival time in the environment. Table 1-7 provides the survival times for major pathogens in soil and on plants.

Pathogens can be destroyed by various treatments, such as heat (high temperature) generated by physical, chemical or biological processes. Sufficient temperatures maintained for sufficiently long time periods can reduce bacteria, viruses, protozoan cysts and helminth ova to below detectable levels (helminth ova are the most resistant to heat treatment). Chemical processing with disinfectants (e.g., chlorine, ozone, lime, etc.) can also reduce bacteria, viruses and vector attraction. High pH conditions, for example, may completely destroy viruses and bacteria but have little or no effect on helminth eggs. Gamma and high energy electron beam radiation treatment depends on dosage with viruses being most resistant. Reduction of pathogenic organisms can be measured using microbiological analysis directly or by monitoring non-pathogenic organisms-indicators.

TABLE 1-7 PATHOGEN SURVIVAL TIME IN THE ENVIRONMENT [15]

Pathogen	Soil		Plants	
	Abs. Maximum	Common Maximum	Abs. Maximum	Common Maximum
Bacteria	1 year	2 months	0.5 year	1 month
Viruses	1 year	3 months	2 months	1 month
Protozoan cysts	10 days	2 days	5 days	2 days
Helminth ova	7 years	2 years	5 months	1 month

Existing regulations require monitoring for representative pathogens and non-pathogenic indicator organisms (fecal coliform bacteria). Direct monitoring is required for the three common types of pathogens: bacteria, viruses and viable helminth ova. [1]

There are test procedures available to determine viability of helminth ova and certain types of enterovirus species. No test procedure is available for bacteria. When direct monitoring of bacteria is important, *Salmonella sp.* are used. They are good indicators of reduction of other bacterial pathogens.

Microorganism density is defined by current regulations as *number of microorganisms per unit mass of total solids (dry weight)* [15].

For liquid biosolids, density is determined as number of microorganisms per 100 milliliters. The microorganisms in biosolids are associated with the solid phase. When biosolids are dewatered, the number of microorganisms per unit volume changes significantly whereas the number per unit mass of solids remains almost constant. Units and methods used to count microorganisms vary (e.g., viable ova are observed and individually counted under a microscope). Viruses are counted in plaque-forming units (PFU). Each PFU is an infection zone were a single virus infected a layer of animal cells.

For bacteria the count is in colony-forming units (CFU) or most probable number (MPN). CFU is a count of colonies on an agar plate and it is not necessarily a count of individual organisms. MPN is a statistical estimate of numbers in an original sample. The sample is diluted at least once into tubes containing nutrient medium; there are several duplicates at each dilution. The original bacterial density in the sample is estimated based on the number of tubes that show growth.

Under existing regulations, the pathogen density limits are expressed as numbers of PFUs, CFUs, or MPN per four (4.0) grams total solids. (This approach was developed because most of the tests start with 100 mL of biosolids which typically contain 4 grams of solids.) Densities of total and fecal coliform, however, are given on a "per gram" basis. [3], [15]

C. Odors and Other Nuisances

Biosolids treatment and management practices are greatly influenced by odor and other pollutant and nuisance factors such as dusts (particulate matter), gaseous and liquid discharges, and vectors (insects, birds, rodents, etc.).

Biosolids are inherently odorous and if handled improperly can create offensive odors and other pollutants and nuisances which may cost a lot of time and money to correct.

Control of odors is one of the most difficult problems in biosolids treatment and management. It is especially true if biosolids are beneficially used.

Dealing with odors and nuisances is often not a technical issue but rather a matter of public acceptance, public education and human perception. Regulatory requirements concerning odors are often poorly defined leaving much room for interpretation and arbitrary action. Odor is an increasingly sensitive subject, and it is one of the first (and frequently most important) issues concerning the public.

1. *Odor Compounds*

Although the exact origin, chemical composition and fate of many odors from biosolids are difficult to classify and not well studied, it is also true that the overwhelming majority of odor compounds are by-products of decomposition and decay of organic matter. Therefore, the most effective control measures are based on preventing or managing this decomposition cycle.

Raw organic material brought by the influent settles into primary solids largely without microbiological decomposition. Primary solids are untreated solids from residential and industrial sources which makes them potentially the most odorous. Secondary solids are primarily products of aerobic microbiological activity.

Microorganisms decompose and metabolize organic matter, decrease the amounts of raw organics and increase organic matter attributable to live and dead microorganisms.

Microbiological decomposition of raw organic materials results in the use of some elements (carbon, nitrogen and others) by microbes, formation of new and modified organic compounds and the release of products such as carbon dioxide, water, hydrogen sulfide, ammonia, methane and considerable amounts of other partially decomposed organic compounds. A significant number of these organic compounds are strong odor pollutants.

Fatty acids (e.g. acetic acid, a.k.a. vinegar), ammonia and amines (organic derivatives of ammonia), aromatic organics based on the benzene ring with nitrogen atom (e.g. indole and skatole), hydrogen sulfide, organic sulfides (e.g. mercaptans) and numerous other organic compounds have been identified as malodorous pollutants.

Classification of these odor pollutants is difficult due to their low concentration, complexity of molecular structure, often short life span in the air, variety of sources and conditions, etc. However, two large groups can be identified: (1) sulfur-containing organic compounds and (2) nitrogen-containing compounds. Mercaptans (general formula C_xH_ySH) comprise a large group of strong odor pollutants in the sulfur containing group along with various organic sulfides (C_xH_yS) and hydrogen sulfide (H_2S). In the nitrogen containing group, various complex amines (C_xH_yNH) are strong odor pollutants along with ammonia (NH_3) and some others containing N, NH_2 radicals. With few exceptions (notably ammonia and some amines), their threshold odor concentration is very low (fraction of ppb). Table 1-8 lists these odor pollutants, their chemical formula and their recognition threshold.

2. *Odor Measurement*

Instrument-based odor detection has been advancing rapidly, able now to detect odors in parts per billion concentration for a significant number of compounds. Instrumental odor detection preferred by the engineering community has a limited use due to the complexity and variety of odors, considerable amount of time and money required and, more importantly, the availability of the human nose, still the best receptor that senses odors better (in some cases three orders of magnitude better) than any instrument has yet been able to do. Therefore, the human nose is still the most common means for detecting and measuring odors.

The human nose provides a subjective odor evaluation and a number of organoleptic methods (i.e., using the human olfactory system) have been developed to improve reliability and to quantify odor compounds. Most common is the "odor panel technique" (ASTM Method E-679).

The odor panel technique involves a panel of four to sixteen members who are exposed to odor samples diluted with odor-free air. The number of dilutions required to achieve a fifty percent positive response from the members is called the threshold odor concentration (TOC) which is considered to be the minimum concentration detectable by the average person. If, for example, nine volumes of diluting air added to one volume of odor sample generate a fifty percent positive response, this pseudo-concentration is reported as ten dilutions to TOC. In this case, the above sample is defined as having an "odor concentration" of ten odor units (10ou). An odorous compound diluted to its TOC has a concentration of 1.0ou. The stronger the odor, the higher is its odor unit number. Several different nomenclatures are used to determine the number of required dilutions: a) the odor unit (ou); b) the effective dose at 50% positive panel response (ED_{50}); c) dilutions to threshold (D/T); d) dilution ratio Z, etc. All of these are essentially the same. The odor unit and ED_{50} are most common units in odor panel technique. The TOC is the minimum concentration of an odorant that will arouse a sensation. A number of different TOCs have been determined. The most common is odor recognition threshold (Table 1-8), i.e. the odorant concentration at which 50% of the odor panel detected the odor.[16]

Odor concentrations in excess of 5ou are easily recognized by most people and, regardless of odor type, represent the threshold level of complaint (distraction threshold) [11]. At 10ou complaints are assured. An ambient air odor concentration of 2ou maximum is often adopted at the plant boundary to avoid public complaint. A number of inherent difficulties are associated with organoleptic odor measurement. Collection and storage of samples is often an unreliable and expensive process; comparing results of different methods is quite confusing. A detailed discussion of odor science, measurements and odor treatment is provided in [11], [16], [17], [19], [20]. Complete elimination of odors may be the goal; however, the best way to avoid complaints is through odor prevention, management and control to acceptably low levels.

- Portable Instrumental Methods: Currently there are several portable instrumental methods that can measure air concentrations of a number of gaseous compounds (ammonia, hydrogen sulfide, etc.) quite accurately even to very low concentrations. For example, to measure H_2S, there are two types of portable instruments: a gel-cell detector which detects H_2S in the 0-100 ppm range and a more sensitive gold film conductivity type able to detect as little as one ppb (e.g., marketed by Arizona Instrument Co.).
- Draeger Detector Tubes: Draeger detector tubes measure one odor compound at a time. A sealed graduated tube contains a special packing which changes color proportionately to the odor compound concentration. Ammonia, hydrogen sulfide, dimethyl sulfide, and some other odors can be detected by

TABLE 1-8 ODOR POLLUTANTS IN BIOSOLIDS [16],[18], [19]

Odor Pollutant	Formula	Approximate Odor Recognition Threshold (ppbv)	Characteristic Odor
I. Sulfur-Containing Compounds			
Hydrogen Sulfide	H_2S	3-5	Rotten eggs
Mercaptans:			
Allyl Mercaptan	$CH_2{\cdot}CH{\cdot}CH_2{\cdot}SH$	0.05	Strong garlic
Amyl Mercaptan	$CH_3{\cdot}(CH_2)_3{\cdot}CH_2{\cdot}SH$	0.3	Putrid, unpleasant
Benzyl Mercaptan	$C_6H_5{\cdot}CH_2{\cdot}SH$	0.2	Unpleasant
Crotyl Mercaptan	$CH_3{\cdot}CH{\cdot}CH{\cdot}CH_2{\cdot}SH$	0.03	Skunk-like
Ethyl Mercaptan	C_2H_5SH	0.2	Decayed cabbage
Methyl Mercaptan	$CH_3{\cdot}SH$	1.0	Decayed cabbage
Propyl Mercaptan	$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}SH$	0.07	Unpleasant
Tert-Butyl Mercaptan	$(CH_3)_3\ C{\cdot}SH$	0.08	Skunk-like
Organic Sulfides:			
Dimethyl Sulfide	$(CH_3)_2S$	2.5	Decayed vegetables
Diphenyl Sulfide	$(C_5H_5)_2S$	<0.05	Unpleasant
Dimethyl Disulfide	$(CH_3)_2S_2$	<0.05	Unpleasant
Others:			
Thiocresol	$CH_3{\cdot}C_6H_4{\cdot}SH$	0.1	Skunk-like
Thiophenol	C_6H_5SH	0.06	Garlic-like
Sulfur Dioxide	SO_2	9.0	Pungent, unpleasant
II. Nitrogen-Containing Compounds			
Ammonia	NH_3	3,000-15,000	Sharp, pungent
Amines:			
Butylamine	$C_2H_5{\cdot}CH_2CH_2{\cdot}NH_2$	10	Ammoniacal
Dibutylamine	$(C_4H_9)_2{\cdot}N{\cdot}H$	16	Fishy
Diisopropylamine	$(C_3H_7)_2NH$	35	Fishy

TABLE 1-8 (CONT.)

Odor Pollutant	Formula	Approximate Odor Recognition Threshold (ppbv)	Characteristic Odor
Dimethylamine	$(CH_3)_2NH$	45	Putrid, fishy
Ethylamine	$C_2H_5NH_2$	800	Ammoniacal
Methylamine	CH_3NH_2	200	Putrid, fishy
Triethylamine	$(C_2H_5)_3N$	80	Ammoniacal
Trimethylamine	$(CH_3)_3N$	50	Ammoniacal
Others:			
Cadaverine	$NH_2{\bullet}(CH_2)_5{\bullet}NH_2$	<1.0	Decaying flesh
Indole	C_2H_5NH	<1.0	Fecal
Putrescine	$NH_2(CH_2)_4{\bullet}NH_2$	<1.0	Putrid
Pyridine	C_6H_5N	3-5	Irritating
Skatole	C_9H_9N	1-2	Fecal
III. Other Hydrocarbons			
Acetaldehyde	CH_3CHO	4.0	Pungent, fruity
Chlorophenol	$Cl{\bullet}C_5H_5O$	0.2	Medicinal

color proportionately to the odor compound concentration. Ammonia, hydrogen sulfide, dimethyl sulfide, and some other odors can be detected by Draeger tubes. Certain compounds present in the air during testing may cause interference and affect the accuracy of the odor measurement by Draeger detector tubes.

- Portable Gas Chromatographs: Portable gas chromatographs are able to analyze many different compounds. Flame ionization (FID) and flame photometric detection (FPD) are used to detect hydrocarbon, nitrogen-containing (by FID) and sulfur-containing organics (by FPD). Detection limits are usually in the 10-200 ppb range [11].
- Mass Spectrometry/Gas Chromatography: Mass Spectrometry/Gas Chromatography (MS/GS) is based on matching a unique mass spectrum of a sample compound with the spectra of different known compounds stored in the library. It is very accurate and sensitive, although a time-consuming and quite expensive methodology.

3. *Odor Control*

Numerous odor control methods are employed in biosolids treatment and disposal. Generally, two fundamental approaches are used:

a. Source control: Elimination, minimization and containing odors at the source or point of use by selecting an appropriate treatment, equipment or handling process; and
b. Removal of odors generated by a process by treating the process exhaust prior to its release into the atmosphere.

Source controls may include the addition of chemicals to suppress generation of odors (e.g., pH adjustment by lime, injection of odor suppressing chemicals, etc.), aeration, and enclosing of the process and handling equipment. Odor removal and reduction techniques include absorption (e.g., scrubbing by water solutions), adsorption (e.g., activated carbon systems), thermal destruction (incineration, afterburning), atmospheric dilution, masking, etc. A more detailed discussion on specific odor controls is provided in Chapters 3, 4, 5, 6 and 7.

D. Other Characteristics

Other biosolids characteristics which have considerable effect on selection and performance of a treatment process and type of equipment are:

- density
- particle size, granularity
- abrasiveness
- angles of repose, fall and slide
- flowability and transportability (rheological properties)
- corrosivity
- adhesion
- compressibility
- hygroscopicity (for dried biosolids)
- presence of foreign matter, grit and fibrous material

1. *Transportability*

Liquid biosolids, which are physically quite similar to water, can be pumped relatively easily using centrifugal, plunger, progressive cavity, diaphragm, piston or other types of pumps.

Liquid biosolids (up to approximately 6% TS) are usually Newtonian fluids, i.e., pressure loss is proportional to the velocity and viscosity under laminar flow conditions. The flow becomes turbulent at certain critical velocity (usually 1.2-2.0 m/sec. or 4-6 ft/sec.).

The pressure drop in pumping liquid biosolids may be up to 25 percent greater than for water. In turbulent regimes, the losses may be two to four times the losses of water.

The transition from laminar to turbulent flow regime depends on the Reynolds number which is inversely proportional to the fluid viscosity. The precise Reynolds number at which the change of regimes occurs is generally uncertain for biosolids.

Thickened (and especially dewatered) biosolids are non-Newtonian fluids which become plastic as dryness increases. This means, among other things, that the pressure losses are not proportional to flow, so the viscosity is not a constant. Special procedures are required to determine losses for these biosolids under laminar and turbulent regimes.

Prior to treatment, liquid biosolids are usually ground. Grinding is essential when pumping with progressive cavity pumps, prior to dewatering, heat treatment, or other processes. Newer designs of grinders are significantly more reliable and durable than types used in the past.

In certain instances in which quality of the end product is very important (e.g., production of pelletized fertilizer), biosolids degritting and foreign matter removal is strongly advisable. For liquid biosolids, degritting and foreign matter removal can be achieved by using cyclone degritters which employ a centrifugal force to remove heavier grit and foreign particles or by using a microscreen separation. In the case of dried biosolids, the foreign matter is usually removed by screening.

Thickened and especially dewatered biosolids are significantly more difficult to transport, meter and store and careful attention should be paid to the selection of pumps, conveyance and storage arrangements.

Piping design is also an important factor. Biosolids piping is rarely less than 150mm (6 inches) in diameter. Deposits quite often develop inside pipes, resulting in an increase of the losses and, unless cleaning measures are implemented, ultimately in failure.

Dewatered biosolids have rather ill-defined characteristics in terms of their flow properties, or rheology. Direct measurement of biosolids' rheological properties (viscosity, Reynolds number, shear stress) is time-consuming, not very informative and, in most cases, does not provide useful information. Many biosolids properties are extremely difficult to predict due to numerous variables involved. For example, it has been observed that dewatered biosolids (in the 35 to 45% TS range) exhibit unique properties which are often referred to as a "glue-like" or "plastic" phase. In that condition, biosolids tend to form a sticky mass, often shaped as large balls. This glue-like material is very difficult to handle, and this condition should be recognized and anticipated when designing biosolids treatment or conveyance.

Mechanical conveyors (predominantly screw and belt type) and, more recently, shaftless screw conveyors and special positive displacement, single and double piston pumps are used to transport dewatered biosolids. Enclosed conveyors and pumps in particular have the important advantage of containing odors.

2. *Storability*

Storage of biosolids is often required to accommodate variations in the rate of biosolids production and to allow accumulation during periods when subsequent processing facilities are not operational (weekends, downtime, etc.). Biosolids storage is also important to ensure uniform feed to various treatment processes such as dewatering, drying, incineration, chemical stabilization, etc.

Short-term liquid biosolids storage may be accomplished in settling and thickening tanks. Long-term liquid biosolids storage can be provided in aerobic and anaerobic digesters, specially designed separate storage tanks or in-ground lagoons. Tanks usually have storage capacity ranging from several hours to a few days while lagoons may provide up to several years of liquid biosolids storage. If storage is for longer periods, biosolids will deteriorate (e.g., turn septic) unless kept under aerobic conditions. Special preservative chemicals, such as chlorine, lime, sodium hydroxide and hydrogen peroxide, have been employed to prevent deterioration but these have met with only limited success. Entirely different problems arise when dewatered biosolids are stored in silos (tanks), lagoons and stockpiles. The most challenging problem in this situation is to select a type of conveyance and a device to remove biosolids from the storage silos without material bridging and ratholing, uneven discharge, etc. Usually screw feeders and various types of "live bottom" storage bins are used with varying degrees of success.

3. *Fuel Value*

Biosolids contain organic material and thus have a fuel value that can potentially be realized. Biosolids heat content is approximately 5,500 kcal/kg (10,000 BTU per pound) of dry volatile solids or 2,500 to 3,000 kcal/kg (4,500 to 5,500 BTU/lb.) of total dry matter. By way of comparison, coal has a fuel value of 7,750 kcal/kg (14,000 BTU/lb.).

4. *Fertilizer Value*

Commercial chemical fertilizers commonly contain nitrogen, phosphorus and potassium (N-P-K) simultaneously or separately. The N-P-K value of very common fertilizer is 8-8-8 (i.e., 8% nitrogen, 8% phosphorus [as P_2O_5] and 8% potassium [as K_2O]). Biosolids on average (on dry weight basis) contain 4% nitrogen, 0.1% to 1.0% phosphorus and an even smaller amount of potassium (an N-P-K 4-1-0).

Organic nitrogen in biosolids is valued commercially higher (typically at $12 to $17 per percent of nitrogen) than chemical fertilizer's nitrogen ($2 to $4 per percentage point).

Biosolids can be land applied as a fertilizer substitute, either directly or as an additive (filler) in the chemical fertilizer mix or in combination with other beneficial products, such as lime, other alkaline materials and sludges, incineration ash, etc. Certain physical requirements (such as density, moisture, amount of dust, particle size, spreadability, uniformity, durability, minimum odors, etc.) must be addressed in order to use biosolids as a fertilizer or fertilizer additive.

Despite considerable amounts of knowledge available for biosolids processing and management, a frustrating and expensive situation may occur if biosolids properties are not fully evaluated on a case-by-case basis. A smoothly running pilot plant, when expanded into a full-scale production process, may unexpectedly fail. It is even more risky to assume that a full-scale operation can succeed on the basis of preliminary information or laboratory studies.

"Experience is the best teacher" is especially true in the sometimes unpredictable world of biosolids processing and disposal with its many variables and potentially costly surprises.

III. BIOSOLIDS TREATMENT FOR BENEFICIAL USE: AN OVERVIEW

A. Beneficial Uses

The organic matter and nutrient content of biosolids make them a valuable resource to use as a fertilizer and soil conditioner for agricultural crops; to improve marginal and reclaim disturbed lands; to increase forest productivity and to stabilize and revegetate forest land devastated by fires or other natural disasters. Biosolids products are very effective in revegetating areas destroyed by mining and dredge spoil areas. Fertilizing highway median strips and use as a landfill daily, maintenance and final cover are additional methods of beneficially using biosolids. While Section 405(e) of the Clean Water Act (CWA) reserves the choice of use and disposal practices to local communities, the U.S. EPA actively supports the beneficial use of biosolids. When quality of biosolids with respect to pollutants is a limiting factor for beneficial use, POTWs can implement or increase local pretreatment efforts to control discharge limits for nondomestic wastewater discharges in accordance with National Pretreatment Standards. Over 2,000 POTWs in the United States established these programs (1992).

The following beneficial use methods are practiced in the U.S.A. [1]:

1. *Application on Agricultural Land*

Approximately 1.17 million dry metric tons, or 21.6% of total biosolids generated in the U.S.A. (5.4 million dry metric tons in 1989), were used to improve soils for agricultural crops and pastures [1]. Liquid biosolids are usually surface applied or injected into the surface layer of the soil. Dewatered and dried biosolids are typically applied to the land surface by equipment similar to that used for applying chemical fertilizers, limestone, and animal manures and then incorporated by plowing or discing (except on pastures). The amount of biosolids applied to agricultural land should conform to agronomic rates designed to 1) provide the amount of nitrogen needed by the crop, 2) minimize the amount of nitrogen leached to the groundwater, and 3) minimize introduction of pollutants (heavy metals, synthetic organic compounds, etc.) into soil.

2. *Application on Non-Agricultural Land*

Non-agricultural land application in 1989 included forest land (32.3 thousand dry metric tons, or 0.6%), public contact sites (166.1 thousand tons or 3.1%) such as parks, golf courses, etc., and reclamation sites (65.8 thousand tons or 1.2%). Disturbed land resulting from both surface and underground mining can be successfully restored by proper application of biosolids. Approximately 1.48 million hectares were disturbed in the USA between 1930 and 1971 and only 40% of this has ever been reclaimed. Disturbed land reclamation in Pennsylvania, Ohio, Kentucky, Illinois, West Virginia, Missouri, Alabama and Florida proved to be an excellent opportunity for beneficial use of biosolids. Liquid, dewatered and dried biosolids can be applied at significantly larger amounts on non-agricultural and disturbed land (up to 180 metric tons per hectare) on a one-time basis. Instead of a nationwide nitrogen standard, application rates are established by permits (usually state-issued) on a case-by-case basis.

3. *Land Application--Sale or Give-Away*

Approximately 12% of biosolids generated in the U.S.A. were sold or given away for use on home gardens, landscaping and similar applications (1989). Presently (1995), biosolids in this category are either composted (500 thousand dry metric tons per year), heat dried and pelletized (350 thousand dry metric tons per year) or alkaline stabilized. Compost and pellets, in particular, are easy to transport and store for considerable periods of time. They are distributed, marketed and used as a bulk ferilizer in agriculture, on lawns, golf courses, ornamentals and home gardens. These biosolids products may also be distributed in various size bags.

Significant increase in the heat dried and pelletized biosolids production occurred in the late 1980's and early 1990's when a number of municipalities renovated (Milwaukee, Wisconsin and Houston, Texas) or started (Boston, Massachusetts; New York, New York; Tampa and Largo, Florida; Cobb and Clayton Counties, Georgia; Baltimore and Hagerstown, Maryland, etc.) new heat drying and pelletizing facilities. Biosolids pellets produced by these facilities are marketed as a bulk organic fertilizer, fertilizer amendment or as a bagged retail product nationwide.

Production of heat dried biosolids pellets has gained in popularity and is projected to increase substantially in the late 1990's to approximately 6% to 7% of total U.S. biosolids generation.

Production of compost and alkaline stabilized biosolids in the USA has also increased substantially in the 1990's.

4. *Biosolids as a Landfill Cover Material*

Another beneficial application of biosolids is as an alternative daily, maintenance and final cover material (ACM) for landfills. A municipal solid waste (MSW) landfill typically uses approximately a six-inch compacted layer to cover the disposed MSW daily and as maintenance and final cover. The 503 Regulations do not establish standards for biosolids used as a landfill cover in municipal solid waste landfills (MSWLF).

Biosolids used as a cover in MSWLF must be suitable for that purpose (40 CFR Part 258). Requirements such as dryness (e.g., passing a paint filter test), granularity, spreadability, compactibility, permeability, toxicity, odor, pathogen and vector attraction control, ability to support vegetation (if used as a final cover) must be complied with for this application. Biosolids chemically stabilized by alkaline materials such as lime, cement kiln dust, fly ash, etc. and usually mixed with earthen materials are used for landfill cover.

Biosolids used as a landfill cover provide the following benefits:

- reduction of vectors and odors
- control of blowing litter
- reduction of the chance and spread of fires
- reduction of the potential for surface and groundwater pollution
- enhancement of aesthetics
- cost savings

Most state regulations do not require that soil be used as daily cover material at MSW landfills. Regulations generally require that the daily cover should use "compacted layer of at least six (6) inches of suitable material" (e.g., Title 35, Subtitle G, Part 807, Illinois Pollution Control Board Regulations).

Biosolids are also used as a final cover material usually mixed with top soil. In order to establish a vegetative cover on a closed landfill, normally about 0.3 to 0.9 meters (one to three feet) of biosolids and top soil mixture (1:1) is applied.