Chapter 10. Land Application of Biosolids

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Introduction

What are biosolids and how are they different from sewage sludge?

Biosolids are solid, semi-solid, or liquid materials resulting from treatment of domestic sewage that have been sufficiently processed to permit these materials to be land-applied safely. The term was introduced by the wastewater treatment industry in the early 1990's and has been recently adopted by the U.S. EPA to distinguish high quality, treated sewage sludge from raw sewage sludge and from sewage sludge containing large amounts of pollutants.

Benefits of land application of biosolids

Biosolids can be considered as a waste or as a beneficial soil amendment. As an alternative to disposal by landfilling or incineration, land application recycles soil-enhancing constituents such as plant nutrients and organic matter. The main fertilizer benefits are through the supply of nitrogen (N), phosphorus (P), and lime (where lime-stabilized biosolids are applied). Biosolids also ensure against unforeseen nutrient shortages by supplying essential plant nutrients [e.g., sulfur (S), manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), molybdenum (Mo), and boron (B)] that are seldom purchased by farmers because crop responses to their application are unpredictable.

For links to web sites that provide detailed information on many aspects of land application of biosolids, see Sukkariyah et al., 2005, at http://www.agnr.umd.edu/users/waterqual/Publications/html_pubs/biosolids_wq_resource_directory.htm.

Production and characteristics of biosolids

How are biosolids produced?

Biosolids are produced primarily through biological treatment of domestic wastewater (Figure 10.1). Physical and chemical processes are often additionally employed to improve the biosolids handling characteristics, increase the economic viability of land application, and reduce the potential for public health, and environmental and nuisance problems associated with land application practices. These processes treat wastewater solids to control disease-causing organisms and reduce characteristics that might attract rodents, flies, mosquitoes, or other organisms capable of transporting infectious disease. The type and extent of processes used to treat wastewater will affect the degree of pathogen reduction attained and the potential for odor generation. Common treatment processes and their effects on biosolids properties and land application practices are summarized in Table 10.1.

Figure 10.1. Schematic diagram of wastewater treatment facility.

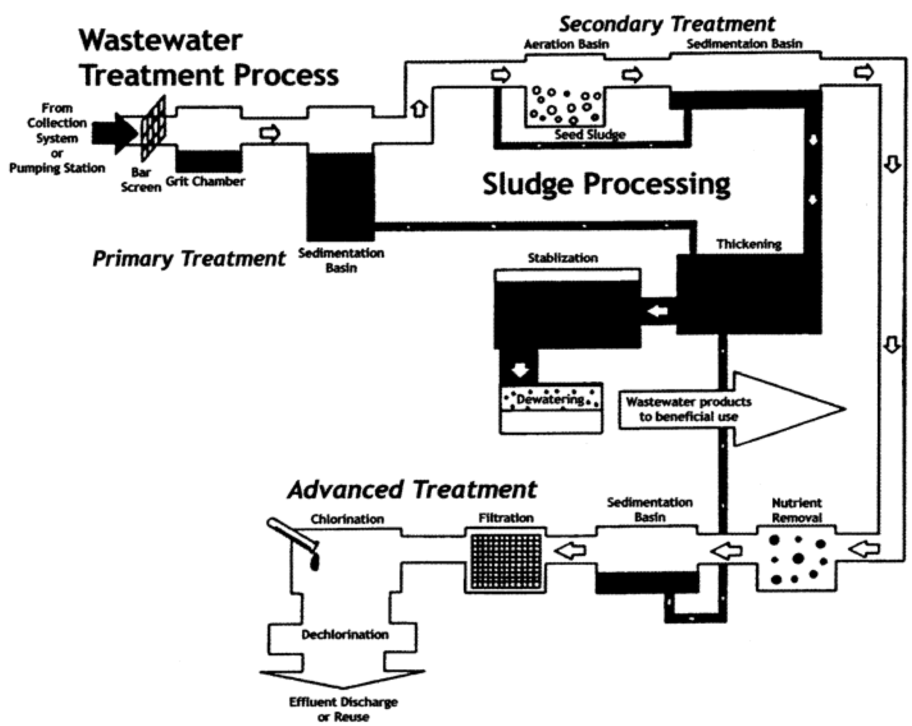

Table 10.1. Description of various wastewater and biosolids treatment processes and methods and their effects on land application practices (Adapted from U.S. EPA, 1984).

Process/Method	Process Definition	Effect on Biosolids	Effect on Land Application Process
Wastewater treatment process			
Thickening	Low force separation of water and solids by gravity, flotation, or centrifugation.	Increase solids content by removing water.	Lowers transportation costs.
Stabilization methods			
Digestion (anaerobic and/or aerobic)	Biological stabilization through conversion of organic matter to carbon dioxide, water, and methane.	Reduces biological oxygen demand, pathogen density, and attractiveness of the material to vectors (disease-spreading organisms).	Reduces the quantity of biosolids.
Alkaline stabilization	Stabilization through the addition of alkaline materials (e.g., lime, kiln dust).	Raises pH. Temporarily decreases biological activity. Reduces pathogen density and attractiveness of the material to vectors.	High pH immobilizes metals as long as pH levels are maintained.
Heat Drying	Drying of biosolids by increasing temperature of solids during wastewater treatment.	Destroys pathogens, eliminates most of water.	Greatly reduces sludge volume.
Chemical and physical processes that enhance the handling of stabilized biosolids			
Conditioning	Processes that cause biosolids to coagulate to aid in the separation of water.	Improves sludge dewatering characteristics. May increase dry solids mass and improve stabilization.	The ease of spreading may be reduced by treating biosolids with polymers.
Dewatering	High force separation of water and solids. Methods include vacuum filters, centrifuges, filter and belt presses, etc.	Increase solids concentration to 15% to 45%. Lowers N and potassium (K) concentrations. Improves ease of handling.	Reduces land requirements and lowers transportation costs.
Advanced stabilization method			
Composting	Aerobic, thermophilic, biological stabilization in a windrow, aerated static pile, or vessel.	Lowers biological activity, destroys most pathogens, and degrades sludge to humus-like material.	Excellent soil conditioning properties. Contains less plant available N than other biosolids.

Characterizing biosolids

The suitability of a particular biosolid for land application can be determined by biological, chemical, and physical analyses. Biosolids' composition depends on wastewater constituents and treatment processes. The resulting properties will determine application method and rate and the degree of regulatory control required. Several of the more important properties of biosolids are:

- *Total solids* include suspended and dissolved solids and are usually expressed as the concentration present in biosolids. The content of total solids depends on the type of wastewater process and biosolids' treatment prior to land application. Typical solids contents of various biosolids' processes are: liquid (2-12%), dewatered (12-30%), and dried or composted (50%).

- *Volatile solids* provide an estimate of the readily decomposable organic matter in biosolids and are usually expressed as a percentage of total solids. Volatile solids content is an important determinant of potential odor problems at land application sites. A number of treatment processes, including anaerobic digestion, aerobic digestion, alkaline stabilization, and composting, can be used to reduce volatile solids content and thus, the potential for odor.

- *pH* and *Calcium Carbonate Equivalent (CCE)* are measures of the degree of acidity or alkalinity of a substance. The pH of biosolids is often raised with alkaline materials to reduce pathogen content and attraction of disease-spreading organisms (vectors). High pH (greater than 11) kills virtually all pathogens and reduces the solubility, biological availability, and mobility of most metals. Lime also increases the gaseous loss (volatilization) of the ammonia (NH_3) form of N, thus reducing the N-fertilizer value of biosolids. CCE is the relative liming efficiency of the biosolids expressed as a percentage of calcium carbonate (calcitic limestone) liming capability.

- *Nutrients* are elements required for plant growth that provide biosolids with most of their economic value. These include N, P, K, calcium (Ca), magnesium (Mg), sodium (Na), S, B, Cu, Fe, Mn, Mo, and Zn. Concentrations in biosolids can vary significantly (Table 10.2), so the actual material being considered for land application should be analyzed.

- *Trace elements* are found in low concentrations in biosolids. The trace elements of interest in biosolids are those commonly referred to as "heavy metals." Some of these trace elements (e.g., Cu, Mo, and Zn) are nutrients needed for plant growth in low concentrations, but all of these elements can be toxic to humans, animals, or plants at high concentrations. Possible hazards associated with an accumulation of trace elements in the soil include their potential to cause phytotoxicity (i.e., injury to plants) or to increase the concentration of potentially hazardous substances in the food chain. Federal and state regulations have established standards for the following nine trace elements: **arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn).**

- *Organic chemicals* are complex compounds that include man-made chemicals from industrial wastes, household products, and pesticides. Many of these compounds are toxic or carcinogenic to organisms exposed to critical concentrations over certain periods of time, but most are found at such low concentrations in biosolids that the U.S. EPA concluded they do not pose significant human health or environmental threats. Although no organic pollutants are included in the current federal biosolids regulations, further assessment of several specific organic compounds is being conducted as has been recommended by the National Research Council (2002).

- *Pathogens* are disease-causing microorganisms that include bacteria, viruses, protozoa, and parasitic worms. Pathogens can present a public health hazard if they are transferred to food crops grown on land to which biosolids are applied; contained in runoff to surface waters from land application sites; or transported away from the site by vectors such as insects, rodents, and birds. For this reason, federal and state regulations specify pathogen and vector attraction reduction requirements that must be met by biosolids applied to land.

Typical nutrient levels in biosolids

There have been very few comprehensive surveys of nutrient levels in biosolids during the past 25 years. One such recent study conducted by Stehouwer et al. (2000) demonstrated that the macronutrient (N, P, and K) concentration of biosolids has changed very little from the late 1970's to the mid 1990's. The data in Table 10.2 represent the means and variability of more than 240 samples collected and analyzed from 12 publicly owned treatment works (POTWs) in Pennsylvania between 1993 and 1997. The POTWs each provided a minimum of 20 analytical records between 1993 and 1997. The 12 POTWs generated between 110 and 60,500 tons of biosolids per year and employed either aerobic digestion (3 facilities), anaerobic digestion (4 facilities), or alkaline addition (5 facilities).

Table 10.2. Means and variability of nutrient concentrations[a] in biosolids collected and analyzed in Pennsylvania between 1993 and 1997 (Stehouwer et al., 2000).

Nutrient	**Total N[b]**	**NH_4-N**	**Organic N**	**Total P**	**Total K**
	----------	----------	%	----------	----------
Mean	4.74	0.57	4.13	2.27	0.31
Variability[c]	1.08	0.30	1.03	0.89	0.27

[a] Concentrations are on a dried solids basis.
[b] Determined as total Kjeldahl nitrogen.
[c] Standard deviation of the mean.

Federal regulations

Introduction

Land application of biosolids involves some risks, which are addressed through federal and state regulatory programs. Pollutants and pathogens are added to soil with organic matter and nutrients. Human and animal health, soil quality, plant growth, and water quality could be adversely affected if land application is not conducted in an agronomically and environmentally sound manner. In addition, N and P in biosolids, as in any fertilizer source, can contaminate groundwater and surface water if the material is overapplied or improperly applied. There are risks and benefits to each method of biosolids disposal and use.

The Part 503 Rule

As required by the Clean Water Act Amendments of 1987, the U.S. EPA developed the regulation, The Standards for the Use or Disposal of Sewage Sludge (Title 40 of the Code of Federal Regulations [CFR], Part 503). This is commonly known as the *Part 503 Rule*. The Part 503 Rule establishes minimum requirements when biosolids are applied to land to condition the soil or fertilize crops or other vegetation grown in the soil. The Clean Water Act required that this regulation protect public health and the environment from any reasonably anticipated adverse effects of pollutants and pathogens in biosolids.

Federal regulations require that state regulations be at least as stringent as the Part 503 Rule. The underlying premise of both the federal and state regulations is that biosolids should be used in a manner that limits risks to human health and the environment. The regulations prohibit land application of low-quality sewage sludge and encourage the application of biosolids that are of sufficient quality that they will not adversely affect human health or the environment. Determination of biosolids quality is based on trace element (pollutant) concentrations and pathogen and vector attraction reduction.

Pollutants and concentration limits

The Part 503 Rule prohibits land application of sewage sludge whose pollutant concentrations exceed certain limits (Table 10.3) for nine trace elements: As, Cd, Cu, Pb, Hg, Mo, Ni, Se, and Zn, Such materials should not be applied to land and are not considered biosolids.

- *Ceiling concentration limits* (CCL) are the maximum concentrations of the nine trace elements allowed in biosolids to be land applied. Sewage sludge exceeding the ceiling concentration limit for even one of the regulated pollutants is not classified as biosolids and, hence, cannot be land applied.

- *Pollutant concentration limits* (PCL) are the most stringent pollutant limits included in Part 503 for land application. Biosolids meeting pollutant concentration limits are subject to fewer requirements than biosolids meeting ceiling concentration limits. Results of the U.S. EPA's 1990 National Sewage Sludge Survey (NSSS) (U.S. EPA, 1990) demonstrated that the mean concentrations of the nine regulated pollutants are considerably lower than the most stringent Part 503 pollutant limits.

- The *cumulative pollutant loading rate* (CPLR) is the total amount of a pollutant that can be applied to a site in its lifetime by all bulk biosolids applications meeting ceiling concentration limits. No additional biosolids meeting ceiling concentration limits can be applied to a site after the maximum cumulative pollutant loading rate is reached at that site for any one of the nine regulated trace elements. Only biosolids that meet the more stringent pollutant concentration limits may be applied to a site once a cumulative pollutant loading rate is reached at that site.

In 1987, the U.S. EPA established pretreatment specifications (40 CFR Part 403) that require industries to limit the concentrations of certain pollutants, including trace elements and organic chemicals, in wastewater discharged to a treatment facility. An improvement in the quality of biosolids over the years has largely been due to pretreatment and pollution prevention programs (Shimp et al., 1994).

Part 503 does not regulate organic chemicals in biosolids because the chemicals of potential concern have been banned or restricted for use in the United States; are no longer manufactured in the United States; are present at low concentrations based on data from the U.S. EPA's 1990 NSSS (U.S. EPA, 1990); or because the limit for an organic pollutant identified in the Part 503 risk assessment is not expected to be exceeded in biosolids that are land applied (U.S. EPA, 1992a). The National Research Council concluded, in their review of the science upon which the Part 503 Rule was based, that additional testing of certain organic compounds should be conducted (National Research Council, 2002). These included poly-brominated diphenyl ethers, nonyl phenols, pharmaceuticals, and other potential carcinogenic and endocrine-pathway disrupting personal care products. Restrictions will be imposed for agricultural use if testing of these organic compounds verifies that biosolids contain levels that could cause harm.

Individual states may impose additional regulations that are at least as stringent as the federal regulations. Links to websites with more information on Mid-Atlantic state regulations can be found on-line at: http://www.agnr.umd.edu/users/waterqual/Publications/html_pubs/biosolids_wq_resource_directory.htm (Sukkariyah et al., 2005).

Table 10.3. Regulatory limits (adapted from U.S. EPA, 1995) and mean concentrations measured in biosolids from the National Sewage Sludge Survey (U.S. EPA, 1990) and a survey of 12 Pennsylvania POTWs between 1993 and 1997 (Stehouwer et al., 2000).

Pollutant	**CCL[a,b]**	**PCL[a,c]**	**CPLR[a,d]**	**Mean[a,g]**	**Mean[a,h]**
	-ppm[f]-	-ppm-	--lbs/A--	--ppm--	--ppm--
Arsenic (As)	75	41	36	10	5
Cadmium	85	39	35	7	3
Copper	4300	1500	1340	741	476
Lead	840	300	270	134	82
Mercury	57	17	16	5	2
Molybdenum	75	[e]	[e]	9	13
Nickel	420	420	375	43	23
Selenium	100	100	89	5	4
Zinc	7500	2800	2500	1202	693

[a] Dry weight basis.
[b] CCL (ceiling concentration limits) = maximum concentration permitted for land application.
[c] PCL (pollutant concentration limits) = maximum concentration for biosolids whose trace element pollutant additions do not require tracking (i.e., calculation of CPLR).
[d] CPLR (cumulative pollutant loading rate) = total amount of pollutant that can be applied to a site in its lifetime by all bulk biosolids applications meeting CCL.
[e] The February 25, 1994 Part 503 Rule amendment deleted the molybdenum PCL for sewage sludge applied to agricultural land but retained the molybedenum CCL.
[f] ppm = part per million.
[g] Data from U.S. EPA, 1990.
[h] Data from Stehouwer et al., 2000.

Pathogen reduction categories

Federal and state regulations require the reduction of potential pathogens and vector attraction properties. Biosolids intended for land application are normally treated by chemical or biological processes that greatly reduce the number of pathogens and odor potential in sewage sludge. Two levels of pathogen reduction, Class A and Class B, are specified in the regulations:

- The goal of *Class A* requirements is to reduce the pathogens (including Salmonella sp., bacteria, enteric viruses, and viable helminth ova) to **below detectable levels**. Class A biosolids can be land applied without any pathogen-related site restrictions. Processes to further reduce pathogens (PFRP) treatment, such as those involving high temperature, high pH with alkaline addition, drying, and composting, or their equivalent are most commonly used to demonstrate that biosolids meet Class A requirements. Biosolids that meet the Part 503 PCLs, Class A pathogen reduction, and a vector attraction reduction option that reduces organic matter are classified as exceptional quality or EQ biosolids.

- The goal of *Class B* requirements is to ensure that pathogens have been reduced to **levels that are unlikely to cause a threat to public health and the environment under specified use conditions**. Processes to significantly reduce pathogens (PSRP), such as digestion, drying, heating, and high pH, or their equivalent are most commonly used to demonstrate that biosolids meet Class B requirements. Because Class B biosolids contain some pathogens, certain site restrictions are required. These are imposed to minimize the potential for human and animal contact with the biosolids until environmental factors (temperature, moisture, light, microbial competition) reduce the pathogens to below detectable levels. The site restriction requirements in combination with Class B treatment is expected to provide a level of protection equivalent to Class A treatment. All biosolids that are land applied must, as a minimum, meet Class B pathogen reduction standards.

Vector attraction reduction

The objective of vector attraction reduction is to prevent disease vectors such as rodents, birds, and insects from transporting pathogens away from the land application site. There are ten options available to demonstrate that land-applied biosolids meet vector attraction reduction requirements. These options fall into either of the following two general approaches: 1) reducing the attractiveness of the biosolids to vectors with specified organic matter decomposition processes (e.g., digestion, alkaline addition) and 2) preventing vectors from coming into contact with the biosolids (e.g., biosolids injection or incorporation below the soil surface within specified time periods).

N, P, and lime application rate

Federal regulations specify that biosolids may only be applied to agricultural land at or less than the rate required to supply the N need of the crops to be grown. This *agronomic rate* is *"designed to provide the amount of N needed by the food crop, feed crop, fiber crop, or vegetation grown on the land; and (2) to minimize the amount of N in the biosolids that passes below the root zone of the crop or vegetation grown on the land to the groundwater"* [40 CFR 503.11 (b)]. Agronomic rate may also be based on crop P needs if it is determined that excessive soil P poses a threat to water quality.

Although not technically a nutrient, lime may also be used as a basis for agronomic biosolids application rate. Biosolids rate may be limited by the CCE when the application of alkaline-stabilized biosolids on an N or P basis may raise soil pH to a level that can induce a trace element deficiency. By signing the land application agreement with a biosolids contractor, the farmer is obligated to make every reasonable attempt to produce a crop on sites receiving biosolids that matches the agronomic rate applied.

Site suitability

Federal, state, and local regulations, ordinances or guidelines place limits on land application based on site physical characteristics that influence land application management practices. These include topography; soil permeability, infiltration, and drainage patterns; depth to groundwater; and proximity to surface water.

Potentially unsuitable areas for biosolids application include:

- areas bordered by ponds, lakes, rivers, and streams without appropriate buffer zones
- wetlands and marshes
- steep areas with sharp relief
- undesirable geology (karst, fractured bedrock) if not covered by a sufficiently thick layer of soil
- undesirable soil conditions (rocky, shallow)
- areas of historical or archeological significance
- other environmentally sensitive areas, such as floodplains

Managing biosolids for agricultural use

Selecting suitable crops for fertilization with biosolids

Crops such as corn, soybean, small grains, and forages have high N assimilative capacities. When these crops are grown on land used for biosolids recycling, the amount of land required when biosolids are applied on an N basis can be reduced. Crops grown for their flowering parts, such as cotton, may produce undesirable amounts of vegetative growth if they continue to accumulate N late in the season, so slow release N sources such as biosolids may not be desirable fertilizer sources for such crops. Biosolids can, however, be used without concern on other crops in rotation with cotton. The tobacco industry, however, has expressly forbidden the use of biosolids for fertilizing tobacco because the crop readily accumulates heavy metals such as Cd.

Biosolids can be applied to vegetable crops, but green leafy vegetables accumulate higher concentrations of metals than do the grain of agronomic crops. Some scientists have cautioned against using biosolids on vegetable crops because they provide a direct pathway of potentially harmful trace elements from the soil to humans, while others (Chaney, 1994) have demonstrated that certain soil and plant barriers exist that prevent trace elements in biosolids of current quality from posing such risks. Regardless of one’s interpretation of the trace element bioavailability evidence, grain and forage crops are better choices for biosolids application than vegetables due to other issues (for example, the time required by regulation between Class B biosolids application and permitted harvesting of crops that can be consumed by humans).

Determining biosolids application rates

Biosolids supply some of all of the essential plant nutrients and soil property-enhancing organic matter. Land application rates, however, are primarily based on the abilities of biosolids to supply N, P, and (in the case of alkaline stabilized materials) lime.

The general approach for determining biosolids application rates on agricultural land is summarized in the following steps:

1. Determine **nutrient needs** for crop yield expected for the soil on which the crop will be grown, and soil test nutrient and pH levels to account for residual nutrient availability.

2. Calculate **biosolids agronomic rates** based on either:
– crop N needs (normally), or
– soil test P levels (if excess P is a problem), or
– soil lime requirement (when lime-supplying biosolids are used and will

raise soil pH above the desirable range if they are applied on an N basis).

3. Calculate **supplemental fertilizer need**s by subtracting the amount of plant-available N, P, and K supplied by biosolids from the crop's N, P, and K needs.

Determining nutrient needs

Fertilizer recommendations are based on the nutrient-supplying capability of the soil and the additional nutrients needed by crops to achieve their potential yield. Soil testing is required prior to the application of biosolids to determine the suitability of soil pH and the availability of P and K. Soil testing can disclose whether limestone, P or K is required for optimum crop productivity. Nitrogen application rates are based on crop N needs for expected yields for a specific soil.

Determining agronomic rates

Biosolids are normally applied at rates to provide the N needed or that which can be assimilated by the crop. This is known as the *agronomic N rate*. Fertilizer N is not normally applied to legumes, which can obtain N from the atmosphere; however, nitrogen assimilative capacity is used to establish agronomic N rates for legumes because they will use biosolids-furnished soil nitrogen. The relative concentrations of nutrients in biosolids are rarely present in the proportions required by the target crop; thus, supplemental fertilization (for example, with K) may be needed to promote optimum vegetative growth and yield.

Biosolids should be applied at rates that supply no more than the agronomic N rate for the specific crop and soil type. One of the systems developed and used in the Mid-Atlantic region to estimate expected yield potential and associated nutrient needs/assimilative capacity is the Virginia Agronomic Land Use Evaluation System (VALUES; Simpson et al., 1993). VALUES and other systems nutrient recommendation systems employed by soil testing laboratories base their fertilizer recommendations on empirical variations in yield potentials of soils for different crops.

Why is the application rate for biosolids usually based on crop N needs?

Nitrogen is required by crops in greater amounts than any other nutrient; thus, the crop's requirement for most other nutrients is normally met when the agronomic N rate is applied. Biosolids rate is further limited to N supplying capacity because N (as nitrate) is the nutrient most likely to be lost to surface and groundwater if applied at greater than agronomic rates.

The following cautions regarding the determination of agronomic N rates should be considered:

- The amount of plant-available N can be underestimated or overestimated because the N composition of biosolids that is used to establish the average N concentration can vary significantly during the period of time that samples are collected and analyzed to establish the agronomic N rate.

- The equations used to calculate plant-available N are not site or source specific, and the actual amounts of plant-available N may vary from the target rates.

These problems occur with other types of organic wastes, such as manures and yard waste composts, and are not unique to biosolids.

What is PAN, and how is it determined?

Only a portion of the total N present in biosolids is available for plant uptake. This *plant available nitrogen* or *PAN* is the actual amount of N in the biosolids that is available to crops during a specified period. Equations for calculating PAN are relatively straightforward, but selecting precise site and source specific availability coefficients and reasonable input values is more challenging. Site-specific data, when available, should always be used in preference to “book” values.

Determining availability of ammonium in biosolids

Nitrogen in biosolids may occur in the ammonium (NH_4^+) or nitrate (NO_3^-) forms that are found in commercial inorganic fertilizers, or in organically-bound forms that are found in materials such as manures and composts. The amount of N that will be available to plants varies for each N form. Nitrate is readily plant-available but is not found in high concentrations in most biosolids. Ammonium is also available to plants, but it can be lost to the atmosphere (via volatilization) as ammonia (NH_3) gas when biosolids are applied to land without prompt incorporation into the soil. The available (non-volatilizable) fraction of NH_4^+-N may be estimated based on the time of incorporation after application. Examples of N availability coefficients from the non-volatized fraction of NH_3 used in Virginia are presented in Table 10.4.

Table 10.4. Examples of estimated plant available percentage of ammonia from biosolids (adapted from Virginia Biosolids Use Regulations - Table 12; Virginia Department of Health, 1997).

Management Practice	**Biosolids with pH lower than 10**	**Biosolids with pH higher than 10**
	------- available % NH_3 -------	
Injection below surface	100	100
Surface application with:		
• incorporation within 24 hours	85	75
• incorporation within 1-7 days	70	50
• incorporation after 7 days	50	25

Determining availability of organic N in biosolids

Organic N must be broken down to NH_4^+ (via mineralization) and NO_3^- (via nitrification) by soil microorganisms before this form of nitrogen is available for plants to use. Organic N can thus be considered to be a slow release form of nitrogen. The amount of PAN from organic N is estimated by using factors established by research (e.g., Gilmour et al., 2003), such as those presented in Table 10.5. The largest portion of organic N in biosolids is converted to plant available N during the first year after application to the soil.

For example, if the values in Table 10.5 are applied to Virginia, the percentages of organic N that will become available for non-irrigated corn uptake (E_{min}) upon mineralization of land-applied biosolids that have been treated via aerobic or anaerobic digestion, alkaline addition or heating are:

- 30% during the first year after application
- 10% of the remaining organic N during each of the second and third years
- 5% of the remaining organic N during the fourth year

The values in Tables 10.4 and 10.5 may not be the most appropriate for all biosolids applied to any soil, but such “book” values are normally used when site specific data are not available. The amounts of available ammonium (NH_4^+) plus the available portion of the organic N are used to calculate the rate of biosolids needed to supply a given amount of plant available N. Equations for calculating PAN are relatively straightforward, but selecting precise site and source specific availability coefficients is an imprecise exercise. Site-specific data should be used if it is available.

Table 10.5. Biosolids organic N mineralization factors recommended by Gilmour et al. (2000, 2003) for annual (K_{min}) and growing season (E_{min}) periods in the Mid-Atlantic states under dryland and irrigated conditions. E_{min} is the effective mineralization factor for the growing season portion of the year. N use efficiency for this period was determined to be 71%.

	---------- Non-irrigated ---------				------------ Irrigated ------------			
State	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 1**	**Year 2**	**Year 3**	**Year 4**
	------------------------------------ K_{min} ------------------------------------							
PA	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
DE	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
MD	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
WV	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
VA	0.42	0.14	0.14	0.07	0.50	0.21	0.14	0.07
	------------------------------------ E_{min} ------------------------------------							
PA	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
DE	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
MD	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
WV	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
VA	0.30	0.10	0.10	0.05	0.35	0.15	0.10	0.05

Will agronomic N rates of biosolids meet all crop nutrient needs?

Agronomic N rates of biosolids do not necessarily meet all crop nutrient requirements. For example, potassium (K) is often recommended for agronomic crops grown in Virginia soils, but the nutrient is present in low concentrations in biosolids. Supplemental K fertilization based on soil testing may be required for optimum plant growth where biosolids are applied.

What problems can be caused by applying biosolids at agronomic N rates?

Biosolids normally supply similar amounts of plant available N and P, but crops require one-fifth to one-half as much P as N. If P in a certain biosolid is largely contained in forms that are readily soluble/plant-available, then applying the biosolids at rates to supply the N needs of crops will eventually supply more P than necessary. Many soils in the Chesapeake Bay region contain very high concentrations of P due to long-term manure application or repeated fertilization with commercial P fertilizer. Long-term application of N-based biosolids rates can increase the potential for P contamination of surface water where soil P concentrations are already high. To alleviate the potential of P runoff or leaching in such cases, it may be advisable to apply the biosolids at rates to meet the P needs of the crop. The need to apply biosolids on a P basis can be verified with the use of a site-specific assessment tool, such as the P Index, which incorporates P transport risk in addition to soil P quantity factors. Applying biosolids on a P basis would likely require a farmer to purchase fertilizer N to meet the crop needs.

How are plant availabilities of P and K from biosolids determined?

The U.S. EPA (1995) estimated that 50% of the total P and 100% of the total K applied in biosolids would be available for plant uptake in the year of application. A Mid-Atlantic regional water quality workgroup has established that the availability of P in biosolids varies widely (i.e., <20% to >80%) according to the composition of P-binding constituents (esp., Al, Fe, and Ca) and the treatment processes to which the wastewater solids are subjected (http://www.agnr.umd.edu/users/waterqual/Publications/pdfs/PSI_white_paper_03_29_05.pdf). Such variability in biosolids P solubility is employed in specialized P application rate recommendations tools, such as the P Site Index (see Chapter 7).

The quantities of available P and K applied to soil with the biosolids may be credited against fertilizer recommendations in the year of application. Any P and K in excess of plant needs will contribute to soil fertility levels that can regularly be monitored via soil testing and taken into account when determining fertilizer recommendations in succeeding years.

Using soil pH and CCE as the basis for determining biosolids rate

Soil pH influences the availability and toxicity of naturally occurring metals and metals applied to soil in biosolids. Most crops grow well in Virginia soils at pH levels between 5.8 and 6.5. Based on previous U.S. EPA guidance, some states require that soils treated with biosolids be maintained at a pH of 6.5 or higher to reduce metal uptake by crops. Federal regulations do not require a minimum soil pH because pH was factored into the Part 503 risk assessment on which the regulation was based (U.S. EPA, 1992b). It is advisable to maintain the pH of agricultural soils where biosolids have been applied in the optimum range for crop growth (i.e., 5.8 to 6.5) to avoid phytotoxicity.

The CCE of the alkaline-stabilized biosolids may be used to determine application rates. The pH of coarse-textured (i.e., sandy) soils can rise rapidly when limed. Deficiencies of manganese in wheat and soybean and zinc in corn have sometimes been caused by excessive liming (pH > 6.8) of coarse-textured, Coastal Plain soils. Application of lime-stabilized biosolids at agronomic N rates to such soils that already have high pH values can induce such deficiencies. Crop yield reductions may result if the deficiency is not corrected, and the N not utilized by the crop can potentially leach into groundwater; thus, alkaline-stabilized biosolids should not be applied at rates that raise the soil pH in Coastal Plain soils above 6.5 and in all other soils above 6.8.

Magnesium deficiencies have been reported in row crops where repeated applications of calcitic (high Ca, low Mg) limestone has reduced soil Mg concentrations. Such soils can be identified by soil testing and should not receive further additions of "calcium only" liming materials, including Ca-based, lime-stabilized biosolids.

Calculating nutrient-based biosolids application rates

Calculating annual agronomic N rate

Annual agronomic N rate calculations	
Step	**Action**
1	Determine N recommendation for the crop based on the expected yield level for the soil. Use state or private soil testing laboratory fertilizer nutrient recommendations or similar tool (e.g., VALUES).
2	Subtract anticipated N credits (i.e., other sources of N) from the recommended N rate, such as: • Residual N from a previous legume crop. • N that has already been applied or will be applied for the crop by fertilizer, manure, or other sources that will be readily available to plants. • Residual N remaining from application of previous by-product (e.g., manure, biosolids).
3	Calculate the adjusted biosolids N rate by subtracting N available from existing and planned sources from total N requirement of crop.
4	Calculate the PAN/dry ton of biosolids for the first year of application using **Equation 1**: $\mathbf{PAN = NO_3\text{-}N + K_{vol}\,(NH_4^+\text{-}N) + K_{min}\,(Org\text{-}N)}$ where: **PAN** = lbs plant-available N/dry ton biosolids. **NO_3-N** = lbs nitrate N/dry ton biosolids. **K_{vol}** = volatilization factor, or plant-available fraction of NH_4-N (Table 10.4). **NH_4-N** = lbs ammonium N/dry ton biosolids. **K_{min}** = mineralization factor, or plant-available fraction of Org-N (Table 10.5). **Org-N** = lbs organic N/dry ton biosolids (estimated by subtraction NH_4-N from total Kjeldahl N).
5	Calculate the amount of biosolids required to supply the crop N needs using this equation: **Dry tons biosolids required/acre = adjusted biosolids N rate (in lbs/acre) ÷ PAN/dry ton biosolids**. Then divide the tons of dry biosolids by the % solids to convert to wet weight of biosolids required.

Calculating annual agronomic P rate

Applying biosolids to meet the P, rather than the N, needs of the crop is a conservative approach for determining annual biosolid application rates. A scientifically sound approach, which accounts for both P availability and P transport, is the use of a tool such as the P Index (see Chapter 7; and). Supplemental N fertilization will be needed to optimize crop yields (except for N-fixing legumes) if biosolids application rates are based on a crop's P needs.

Calculating agronomic lime requirement

Application rates for lime-stabilized or lime-conditioned biosolids may be computed by determining the biosolids' CCE. The CCE provides a direct comparison of the liming value of the biosolids with calcium carbonate limestone, which is the basis for soil testing liming requirements. Biosolids conditioned or stabilized with lime may have a CCE between 10 and 50% on a dry weight basis. The agronomic lime rate for a biosolid can be determined by using **Equation 2**:

Dry tons biosolids per acre =
tons of CCE required/acre ÷ biosolids CCE/100

Example: Determining N, P, and lime agronomic rates for a specific situation

A lime-stabilized biosolid has a pH>10, a CCE of 40%, a NO_3-N concentration of 1,000 ppm (0.1%), an NH_4-N concentration of 2,000 ppm (0.2%), a TKN concentration of 27,000 ppm (2.7%), and a total P concentration of 21,000 ppm (2.1%), all on a dry weight basis (% dry solids is 17.6%). Corn for grain is to be grown on a Kempsville sandy loam soil that has a pH of 6.2, "high" K, Ca, and Mg soil test ratings, and a "very high" P soil test rating. The biosolids will be surface-applied and disked into the soil within 24 hours. How can the agronomic rate of the biosolid be determined?

Determining N, P, and lime-based agronomic rates	
Step	**Action**
1	Determine N recommendation for the crop based on the expected yield level for the soil. The estimated yield potential of corn grown on a Kempsville soil according to one method (VALUES) is 120 bu/acre (Simpson et al., 1993), which should require about 132 lbs N/acre (assumption: 1.1 lbs N per bu of corn).

2	Calculate the N-based agronomic rate (using **Equation 1**) by: a) Calculating the components of PAN in the biosolid: NO_3-N = 1,000 ppm x 0.002 = 2 lbs/ton NH_4-N = 2,000 ppm x 0.002 = 4 lbs/ton TKN = 27,000 ppm x 0.002 = 54 lbs/ton Org-N = 54-(2 + 4) = 48 lbs/ton b) Calculating PAN: PAN = 2 + 0.75 (4 lbs/ton) + 0.3 (48 lbs/ton) = 2 + 3 + 14.4 = 19.4 lbs/ton c) Dividing the adjusted fertilizer N rate (132 lbs N/dry ton) by the PAN/dry ton biosolid (19.4 lbs N/dry ton) to obtain the agronomic N rate (6.8 dry tons/acre).
3	Calculate the P-based agronomic rate using your state's P Site Index.
4	Calculate the lime-based agronomic rate: The coarse-textured Kempsville soil requires 0.75 tons limestone/acre to raise the pH to 6.5 (Donohue and Heckendorn, 1994). Use **Equation 2** to determined the rate of lime-stabilized biosolids needed to provide 0.75 tons CCE/acre: Lime-based biosolids rate = tons of CCE required/acre ÷ biosolid's CCE/100 (0.75 tons CCE/acre) ÷ 40%/100 = 1.88 dry tons/acre.
5	Compare the rates calculated in the steps above: The N- and lime-based agronomic rates for the example above are 6.8 and 1.9 dry tons/acre, respectively. Dividing each of these rates by the fraction of solids in the biosolids (0.176) gives the wet weights of biosolids that must be applied to meet N- (39 wet tons/acre) and lime-based (11 wet tons/acre) application rates. No P (and, thus, no biosolids) would be recommended to meet plant P needs; however, a tool such as the P Index can be employed to calculate at what rate biosolids can be applied in an environmentally sound manner. Finally, the capability of equipment to spread very low rates and the economics of applying low rates may prevent biosolids from being applied at all.

Land application methods

Introduction

The most appropriate application method for agricultural land depends on the physical characteristics of the biosolids and the soil, as well as the types of crops grown. Biosolids are generally land- applied using one of the following methods:

- sprayed or spread on the soil surface and left on the surface for pastures, range, and forest land; or.
- incorporated into the soil after being surface- applied or injected directly below the surface for producing row crops or other vegetation.

Both liquid and dewatered (or "cake") biosolids may be applied to land with or without subsequent soil incorporation.

Applying liquid biosolids

Liquid biosolids can be applied by surface spreading or subsurface injection. Surface methods include spreading by tractor- drawn tank wagons, special applicator vehicles equipped with flotation tires, or irrigation systems. Surface application with incorporation is normally limited to soils with less than a 7% slope. Biosolids are commonly incorporated by plowing or disking after the liquid has been applied to the soil surface and allowed to partially dry, unless minimum or no-till systems are being used.

Spray irrigation systems generally should not be used to apply biosolids to forage or row crops during the growing season, although a light application to the stubble of a forage crop following a harvest is acceptable. The adherence of biosolids to plant vegetation can have a detrimental effect on crop yields by reducing photosynthesis and provides a more direct pathway for pollutant consumption by grazing animals. In addition, spray irrigation increases the potential for odor problems and reduces the aesthetics at the application site.

Liquid biosolids can also be injected below the soil surface using tractor-drawn tank wagons with injection shanks and tank trucks fitted with flotation tires and injection shanks. Both types of equipment minimize odor problems and reduce ammonia volatilization by immediate mixing of soil and biosolids. Injection can be used either before planting or after harvesting crops, but it is likely to be unacceptable for forages and sod production. Some injection shanks can damage the sod or forage stand and leave deep injection furrows in the field.

Subsurface injection will minimize runoff from all soils and can be used on slopes up to 15%. Injection should be made perpendicular to slopes to avoid having liquid biosolids run downhill along injection slits and pond at the bottom of the slopes. As with surface application, drier soil will be able to absorb more liquid, thereby minimizing downslope movement.

Applying dewatered biosolids

Dewatered biosolids can be applied to cropland by equipment similar to that used for applying limestone, animal manures or commercial fertilizer. Typically, dewatered biosolids will be surface-applied and incorporated by plowing or another form of tillage. Incorporation is not used when applying dewatered biosolids to forages. Biosolids application methods such as incorporation and injection can be used to meet Part 503 vector attraction reduction requirements.

Timing of biosolids application

The timing of biosolids application must be scheduled around the tillage, planting, and harvesting operations and will be influenced by crop, climate, and soil properties. Traffic on wet soils during or immediately following heavy rainfalls may cause compaction and leave ruts in the soil, making crop production difficult and reducing crop yields. Muddy soils also make vehicle operation difficult and can create public nuisances by carrying mud out of the field and onto roadways.

Applications should also be made when crops will soon be able to utilize the N contained in the biosolids. Failure to do so could result in potential nitrate contamination of groundwater due to leaching of this water-soluble form of nitrogen. It is advisable that biosolids applied to land between autumn and spring have a vegetative cover (i.e., permanent pasture, winter cover crop, winter annual grain crop) to reduce erosion of sediment-bound biosolids, runoff of N, P, and pathogens, and leaching of nitrate.

Split applications may be required for rates of liquid biosolids (depending on the solids content) in excess of 2-3 dry tons/acre. Split application involves more than one application, each at a relatively low rate, to attain a higher total rate when the soil cannot assimilate the volume of the higher rate at one time.

Biosolids storage

In-field storage of biosolids at or near the application site is often needed. Storage facilities are required to hold biosolids during periods of inclement weather, equipment breakdown, frozen or snow-covered ground, or when land is unavailable due to growth of a crop. Liquid biosolids can be stored in digesters, tanks, lagoons, or drying beds; and dewatered biosolids can be stockpiled. Recommended guidelines for such storage have been specified by the U.S. EPA (2000).

Disadvantages of land application

Large land areas may be needed for agricultural use of biosolids because application rates are relatively low. Transportation and application scheduling that is compatible with agricultural planting, harvesting, and possible adverse weather conditions require careful management.

Biosolids are typically delivered to the application site by tractor trailers containing approximately 20 tons. At a solids content of 15-25%, this is approximately 3-5 dry tons per trailer, or about the amount of biosolids that is normally spread onto one acre of land for crops such as corn, soybean or wheat. Therefore, there will be considerable truck volume over the course of several weeks for large sites of several hundred acres. Increased traffic on local roads, odors, and dust are potential impacts on the local community that should be addressed by notifying neighbors in public informational meetings or public hearings. Working out delivery schedules that are least likely to be disruptive will minimize the problems caused by biosolids transportation.

Biosolids, even when properly treated, will have odors. Under unfavorable weather conditions, the odors may be objectionable, even to rural communities accustomed to the use of animal manure. Odors may be reduced by stabilization process, application method, storage type, climatological conditions, and site selection, as described below.

- Stabilization reduces the biological activity and odor of biosolids. The products of aerobic digestion, heat treatment, and composting tend to result in the least objectionable odors. Anaerobic digestion has the potential to cause more odor than other treatment methods if not performed properly. Likewise, lime-stabilized biosolids, the most commonly used material in the state, may generate odors if not properly stabilized and managed.

- Application method affects the odor potential at the site. Immediate soil incorporation or direct soil injection will reduce the potential for odor problems.

- Biosolids storage can occur at the treatment plant, the site of application, or a temporary facility. Storage at the treatment plant (if isolated from the public) is the preferred method. Off-site storage requires proper site selection and management to minimize the potential for odor problems.

- Weather conditions (i.e., temperature, relative humidity, wind) will affect odor severity when biosolids are surface-applied. Spreading in the morning when air is warming and rising will help dilute the odor in the immediate vicinity.

- The selection of the application site is important to the success of the operation. Ideally, the site should be located away from residential areas.

Objectionable odors will sometimes be present despite adequate stabilization processes and favorable weather conditions. Complaints can be expected if adjacent property owners are subjected to persistent odors. A well-managed system with the proper equipment and stabilized biosolids will substantially reduce the potential for unacceptable odors.

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