Activity and Movement of Plant Nutrients and Other Trace Substances

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Biosolids is the term for an organic fertilizer or soil amendment produced by the treatment of domestic wastewater. Domestic wastewater treatment and disposal are evident in archaeological digs, but the practice of community-wide treatment did not evolve until the late 19th century.

Since then, wastewater treatment technology has advanced. Many new publicly owned treatment works (POTWs) were built with federal help.

As communities face stricter regulations against polluting land and streams, more industries will remove their contaminants before passing the waste on to the community. The resulting biosolids and effluents can be applied to land as nutrient and water sources.

Wastewater coming into the treatment plant is screened (primary treatment). The solids are broken down biologically (secondary treatment). If this process includes air (aerobic), the solids produce carbon dioxide and microbial bodies (biosolids). If treated without air (anaerobic), the waste is reduced to ammonia, methane and microbial bodies. Lime, alum or other material is added to stabilize the product. The microbial bodies and most of the phosphorus drop out, producing biosolids. The remaining effluent then enters the streams, nearly free of contaminants.

Land application

Applying biosolids to land is a popular disposal method. In 1942, Rudolfs and Gehm documented the agronomic attributes of sludge. They also identified copper, zinc, lead and chromium in the waste.

The environmental movement of the 1970s made us more concerned about waste disposal methods and use of biosolids. In the past 20 years, scientific knowledge about treatment processes and waste has expanded.

Soil application and leaching, food chain effects and human health effects were major issues identified at a 1973 workshop, sponsored by the U.S. Environmental Protection Agency (EPA), U.S. Department of Agriculture and the National Association of Land Grant Colleges. Long-term research projects began to assess the impact of heavy metals on soils, plants and the human food chain. Many of these studies continue today.

Researchers identified arsenic, cadmium, mercury, lead, selenium and zinc as a concern of the human food chain. Boron, cadmium, copper, nickel and zinc were targeted for phytotoxicity.

Trace elements in biosolids

Laboratory and field studies demonstrate that most trace elements are relatively immobile in soils. Once added to the soil, they remain where they are put, except under certain pH conditions. Groundwater contamination is not likely, except in very sandy soils.

Field studies show that greenhouse studies grossly overstated the availability and phytotoxicity of metals in biosolids.

A field study report shows movement of cadmium from soil to plant to grain (Table 1). The untreated control demonstrates cadmium uptake from the natural geochemical levels that exist in soils. During a 1982 MU project, researchers identified cadmium at 0.0114 pounds per dry ton (5.7 ppm), chromium at 0.08 pounds per dry ton (40 ppm), nickel at 0.36 pounds per dry ton (18 ppm) and zinc at 0.38 pounds per dry ton (190 ppm) in untreated soils (Table 2).

Table 1
Cadmium transfer from soil to corn plant to seed in soils treated with biosolids (Reference 1)

Cadmium levels		
	Corn fodder (parts per million)	**Corn grain (parts per million)**
Control fertilizer	0.38	Not detected
20 + 60 + 60	0.38	Not detected
Sludge		
5 tons per acre	0.93	Not detected
10 tons per acre	1.22	Less than 0.10
15 tons per acre	1.28	0.10
20 tons per acre	1.28	0.10

Table 2
Summary analysis of Missouri wastewater biosolids.[2]

Element	**Range (pounds per dry ton)**	**Median (pounds per dry ton)**

Arsenic	less than 0.01 to 0.08	0.01
Beryllium	less than 0.01 to 0.01	less than 0.01
Boron	0.02 to 0.76	0.07
Cadmium	less than 0.01 to 0.64	0.02
Calcium	26 to 560	78
Chromium	0.02 to 24	0.17
Copper	0.09 to 10.4	0.78
Iron	6 to 82	32
Lead	0.08 to 1.9	0.29
Magnesium	3 to 42	0.92
Manganese	0.12 to 13.6	0.92
Mercury	0.01 to 0.26	0.07
Molybdenum	less than 3 to 15	less than 3
Nickel	0.02 to 26	0.07
Nitrogen	8 to 106	54
Phosphorus	7 to 102	32
Potassium	0.5 to 22	5.3
Selenium	less than 0.1 to 0.05	0.01
Silver	less than 0.7 to 3	less than 0.7
Sodium	0.42 to 100	2.9
Zinc	0.34 to 26	2.4
PCB	0.002 to 0.006	0.002
Chlordane	0.009 to 0.02	0.006

Other organic compounds tested were aldrin, BHC, DDE, DDT, dieldrin, endrin, heptepox and lindane. The median concentration of these were 0.1 parts per million (ppm). The range was 0.005 - 0.81 ppm.

Plant nutrients in biosolids

While questions remain, there is adequate information to let us take advantage of the plant nutrients in biosolids. As a safeguard, federal and state regulations define the pollutant loading limits for application.

In 1982, Missouri wastewater treatment plants were screened to identify the presence of various elements in the waste.

The units used in Table 2 are pounds per dry ton. This removes the confusion of dilution effects from water present in the material applied to the land. Expressing terms in dry weight makes it easier to compare materials from different sources. Much like fertilizer applied by a dealer is expressed in pounds of dry material applied, so are biosolids.

The 72 treatment plants produced biosolids that provided an average of 78 pounds of calcium, 54 pounds of nitrogen and 32 pounds of phosphorus in each dry ton. Most potassium compounds are soluble and leave the POTW in the effluent.

For example, to fertilize a corn crop, you need about 3 dry tons per acre, but other elements are applied, as well.

The 0.02 pounds of cadmium applied per ton results in 0.06 pounds applied to the soil, which is far less than that detected in the fodder as shown in Table 1.

You might ask, "How much would be transferred to an animal eating the fodder?" One ten-millionth of that in the soil found its way to a goat's liver.

A test conducted by Brams, Anthony and Weatherspoon shows that if a human eats 8 ounces of fresh liver from an animal with the highest level of cadmium, only 0.03 percent of the daily tolerable intake of cadmium in the human diet is consumed (Reference 3). This proves to be a reasonable risk, even for those who eat more liver than the average consumer.

Reactions in the soil

Reactions in the soil explain what happens to the elements listed in Table 2 when biosolids are applied to the land. There are many — to discuss each would require a book. However, a few reactions will explain what happens to most.

Mineralization
The biosolids are mostly made of microbial bodies that contain carbon (C), oxygen (O), hydrogen (H), nitrogen (N), sulfur (S) and phosphorus (P).

Soil organisms attack the dead microbial bodies through decomposition. This produces carbon dioxide (CO_2), water (H_2O) and humus (organic matter).

The release, or mineralization, of N as ammonium (NH_4N), P as phosphate and S as sulfate occurs, also. The ammonium nitrogen may also be oxidized to produce nitrate (NO_3). These can be taken up by plants and reused.

Cation exchange
The process allows the negative charges of the soil clay and humus to hold positively charged elements (cations). The cation exchange capacity measures the soil's ability to hold cations. The following are or become cations upon release (mineralization) from biosolids:

Cadmium (Cd), calcium (Ca), chromium (Cr), copper (Cu), lead (Pb), magnesium (Mg), mercury (Hg), nickel (Ni), potassium (K), sodium (Na) and zinc (Zn).

All will be held by cation exchange and tend not to leach.

Anion exchange and retention
This accounts for the way that anions (negatively charged ions) are sorbed or attached to the soil. Upon biosolids mineralization, arsenate (AsO_4-^{3}), borate (BO_3), nitrate (NO_3), phosphate (PO_4-^{3}) and selenate (SeO_4-^{3}) are the most anionic forms of Arsenic (As), boron (B), N, P and selenium (Se).

As a group, AsO_4-^{3}, PO_4-^{3} and SeO_4-^{3} behave similarly. They may be sorbed on the surface of the soil by several different mechanisms, making these anions quite immobile. The three anions are held where they are placed.

In contrast, borate and nitrate are very mobile and will move readily through the soil in the direction the soil moisture moves.

Soil acidity
Soil pH also effects the elements in Table 2. Regulations require soil pH be greater than 6.0 (salt-based test) before applying biosolids. If the soil pH is below 6.0, many metals, such as Cd, Cr, Cu and Zn become more plant available. As pH rises, almost all of the elements listed in Table 2 revert to forms unavailable to plants. In spite of this, you should not raise the soil pH above 7.5 because it may cause plant nutrient deficiencies, such as iron (Fe) and manganese (Mn).

In summary, mineralization, cation exchange, anion exchange, retention and soil pH adjustment may affect the availability of elements in the biosolids. The minimum availability of most metals in Table 2 occurs at a soil pH of 6.0 to 7.5.

Remember, soils are natural bodies that develop from rocks, containing all the elements in Table 2. There is no such thing as a natural soil free of metals.

Agronomic rates

Applying biosolids at the proper application rate that satisfies crop yield goals reduces the risk of excessive non-essential elements.

Agronomic rates are tied to the nitrogen needs of the crop. As with nitrogen fertilizer, the farmer sets a yield goal. The goal determines the nitrogen rate. Formulas convert the biosolids analysis into the quantity of available N per dry ton. The factors change for different biosolids.

For example, assume you wish to grow 4 tons of grass hay per acre. Forty pounds of N is needed per ton of hay or 160 pounds N per acre (4 x 40).

If the biosolids have 3 percent N per dry ton, then they have 60 pounds N per ton. If 40 percent of the N is available the first year, then the application rate in dry tons of biosolids will be as follows:

160 pounds N ÷ (0.4 x 60 pounds N per ton) = 6.6 tons per acre

If you use the medium potassium concentration of Table 2, the 6.6 tons of dry biosolids will supply 35 pounds K per acre (42 pounds K_2O per acre). This is less than is needed for 4 tons of grass hay, so you must apply more K.

The biosolids supplier can provide laboratory analysis of the material produced by the treatment plant. Apply this application rate to other elements in the material.

Table 3
Summary analysis of biosolids in national survey

Name	Minimum	Median	95 percentile
Aluminum	363.0	8510.00	44900.0
Arsenic	0.3	6.85	36.1
Barium	2.2	507.00	1480.0
Beryllium	0.1	0.50	1.6
Boron	2.1	19.10	163.0
Cadmium	0.7	8.30	124.0
Calcium	165.0	27800.00	142000.0
Chromium	2.0	94.10	1230.0
Cobalt	3.9	9.85	31.3
Copper	6.8	473.00	1930.0
Iron	77.3	15300.00	58900.0
Lead	9.4	143.00	486.0
Magnesium	250.0	4260.00	11800.0
Manganese	8.5	393.00	1880.0
Mercury	0.2	2.50	11.3
Molybdenum	2.0	9.15	42.4
Nickel	2.0	36.70	272.0
Phosphorus	1670.0	12235.00	22800.0
Potassium	620.0	620.00	620.0
Selenium	0.5	4.60	15.2
Silicon	694.0	1247.00	1800.0

Silver	1.5	43.75	150.0
Sodium	26.5	1520.00	16000.0
Strontium	47.4	110.70	174.0
Sulfur	3290.0	5985.00	8680.0
Thallium	0.2	1.1	10.1
TKN (Total Kjeldahl Nitrogen)	30.0	43200.0	92600.0
Tin	3.1	54.1	383.0
Titanium	4.2	106.0	789.0
Vanadium	2.1	16.7	155.0
Zinc	37.8	892.0	3720.0

Table 4
Average total concentrations of elements in Missouri soils

Element	Geometric	Observed range
AG	<0.7	<0.7 to 3
Al, pct**	4.1*	1.1 to 7.9
As	8.7	2.5 to 72
B	31	<20 to 700
Ba	580	100 to 1500
Be	0.8	<1 to 2
C (as total), pct	1.30	0.24 to 5.2
C (as carbonate), pct	0.028	<0.01 to 2.9
C (as organic), pct	1.25	0.08 to 5.2
Ca, pct	0.33	<0.07 to 5.6
Cd	<1	<1 to 11
Ce	115	<150 to 300
Co	10	<3 to 30
Cr	54	10 to 150
Cu	13	5 to 150

F	270	10 to 6400
Fe, pct	2.11*	0.49 to 5.4
Ga	11	<5 to 30
Hg	0.039	<0.01 to 0.8
I	4.4*	1.2 to 11.7
K, pct	1.4*	0.33 to 3.7
La	41	<30 to 150
Li	22	7 to 47
Mg, pct	0.26	0.05 to 2.8
Mn	740	15 to 3000
Mo	<3	<3 to 15
Na, pct	0.53*	0.07 to 1.2
Nb	7.2	<10 to 15
Nd	63	<70 to 150
Ni	14	<5 to 70
P, pct	0.059	<0.01 to 0.61
Pb	20	10 to 7000
Sc	7.6	<5 to 15
Si, pct	35*	23 to 43
Sn	<15	<15 to 50
Th	9.6*	3.2 to 21
Ti	3300	1500 to 7000
U	3.8	1.1 to 15
V	69	15 to 150
Y	32	<10 to 70
Yb	3.2	<1 to 7
Zn	49	18 to 640
Zr	310	70 to 700

*** arithmetic mean**
**** one-hundredth part**

References

- Naylor, L.M., M. Barmasse, and R.C. Loehr, "Uptake of Cadmium and Zinc by Corn on Sludge-Treated Soils," Biocycle 28:37-41, April 1987.
- Clevenger, Hemphill and Roberts, *Chemical Compositions of Municipal Sewage Sludges in Missouri,* 1982. MU Environmental Tract Substances Resource Center, Columbia, Mo. 65201.
- Brams, Anthony and Weatherspoon, *Treated Soil to Hay to Goat to Liver,* 1989. J. Environ. Quality, volume 18: 317-323.
