Biosolids in Vegetable Production Systems

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Summary. Land application and landfilling are the most common destination for biosolids in the United States. When properly treated and managed in accordance with the existing state and federal regulations and standards, biosolids are safe for the environment and human health. Application of biosolids in vegetable production as an organic amendment to soils can increase plant growth and produce comparable crop yields with less inorganic nutrients than a standard program of commercial synthetic fertilizers. No application rate of treated biosolids alone will produce crop yields equivalent to commercial fertilizers. Biosolids may be used in conjunction with fertilizer thus lessening the application rate required. The major obstacles to public acceptance are issues concerning water pollution, risk of human disease, and odors. Additionally, heavy metals are an issue of bias with public perception. To ensure safe use of biosolids to a vegetable production systems the agronomic rate (nutrient requirement of the vegetable crop grown) should be calculated before application for the specific crop.

In 1998, the amount of biosolids (previously known as sewage sludge) produced in the United States was about 6.9 million tons (6.3×10^6 t), a dramatic increase from 4.6 million tons (4.2×10^6 t) in 1972 [U.S. Environmental Protection Agency (USEPA), 1999]. Today, about 60% of the annual production is used beneficially [direct land applied (spreading the biosolids on the surface of the soil or incorporating or injecting into the soil), composted, or used as landfill cover]. The beneficial use of biosolids should increase due to recycling benefits, competitive cost, and with education to produce a positive public perception (USEPA, 1999). It is estimated that the amount of biosolids produced will increase steadily, rising as high as 8.2 million tons (7.4×10^6 t) in 2010, and that the amount beneficially used will also increase to 70% (USEPA, 1999). Biosolids can be used beneficially by nurseries, landscapers, soil blenders, homeowners, city parks, and in horticulture production.

Biosolids, also known as sewage sludge, are a byproduct of specially treated, stabilized and disinfected waste water and human waste that originate from household wastewater, industrial wastewater, and storm water runoff. Pretreatment regulations require that industrial plants treat or remove any contaminants from wastewater before it is discharged to a municipal treatment plant (plastics, rags, rocks, etc.).

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The raw materials (sewage sludge) from the previous stages must be processed further to produce biosolids. The treatment objectives are to kill disease-causing organisms such as bacteria and viruses, and reduce odors. The most common process to significantly reduce pathogens include (USEPA, 1994, 1995) the following.

Anaerobic digestion involves the use of a sealed, oxygen-free container (the digester) and anaerobic bacteria. The bacteria ferment the waste in the digester, producing methane-rich biogas, fiber and nutrient rich waste water which can be used as liquid fertilizer additive.

Aerobic digestion is similar to anaerobic digestion, but it is in an oxygen rich environment such as a tank or lagoon. The tank or lagoon may be aerated naturally or mechanically.

Composting is a biological decomposition process where microorganisms convert raw organic materials into relatively stable humus-like material. During decomposition, microorganisms assimilate complex organic substances and release inorganic nutrients (Metting, 1993). May occur with biosolids only, or in association with yard trimmings or urban plant debris (YT), municipal solid waste (MSW), wood chips, and food waste or other carbon rich waste materials. The process itself can take place using in-vessel (rely on a variety of forced aeration and mechanical turning techniques to speed up the process), static aerated pile (a blower to supply air to the composting materials and no turning or agitation of the materials occurs once the pile is formed) or windrow (consists on placing the mixture of raw materials in a long narrow piles or windrows which are agitated or turned on a regular basis) composting methods. During a windrow composting the temperature of the biosolids is raised to 55 °C (131 °F) or higher. This temperature is maintained for at least 5 d to kill pathogen with in-vessel composting method and 15 d with a windrow composting method and be turned five times during this time period.

Heat treatment uses active or passive dryers to remove water from biosolids. Through this process, pathogens can also be destroyed.

Lime is added to the biosolids to raise the pH to acceptable soil amendment levels after 2 h of contact.

Air-drying biosolids may be dried on sand beds or in paved or unpaved basins. Biosolids dry for a minimum of 3 months with an ambient average daily temperature above 0 °C (32 °F).

Plant nutrients in biosolids

The water content of biosolids can range from liquid to dried (99 to 5% moisture) depending on the stabilization process used [Table 1 (Obreza and Ozores-Hampton, 1999)]. Because of biosolids variability, it can be difficult and complicated to make recommendations regarding their use as compared with conventional fertilizer. Biosolids have a near-neutral to alkaline pH, a C to N ratio below 10, and contain from 1% to 5% N and phosphate (P_2O_5) (Obreza and Ozores-Hampton, 1999).

Composted biosolids can be a variable when other carbon materials are blended with it for the composting process. Biosolids are often mixed with YT, MSW, wood waste, and food waste to create a cocompost (composting two or more materials together), because the N added by the biosolids accelerates the raw material composting process (Table 2). One of the most popular materials is YT since many states such as Florida could no longer accept it in a Class I landfill, so cocomposting with biosolids can become an attractive option. Liquid biosolids generally are applied via sprinklers or spreader trucks. Solid products usually are applied with manure spreaders.

Regulations governing biosolids application to vegetable crops

In 1992, the USEPA reported increasing evidence that the majority of the biosolids (70%) used in agriculture as fertilizers or soil conditioners meet acceptable standards of safety (Kidder and O'Connor, 1993). Presently, biosolids and biosolids mixed with either YT or MSW are regulated at the Federal level under Clean Water Act Section 503 (USEPA, 1994, 1995). There are 18 states that have regulations in place that are more restrictive than Part 503 regulations concerning pollutant concentration, therefore state and federal regulations should be followed (Goldstein, 2000).

Clean Water Act Section 503 classified two biosolids quality with respect to the nine regulated pollutant elements concentration limit as the

Table 1. Average composition and cost of various biosolids (Obreza and Ozores-Hampton, 1999).

Material	Solids (%)	pH	C:N ratio	N (%)	Phosphoric acid (%)	Cost ($/ton)[z]
Slurry	1	6.6	7	2.3	3.1	<1
Cake	17–30	7.4–8.4	6–8	1.0–7.6	0.2–3.0	0–5
Lime treated	66	12	13	1	1	9
Pellets	94	7	7	4.5	4.0	90

[z]$1/ton = $ 1.10/t.

Table 2. Average composition and cost of various composts (Obreza and Ozores-Hampton, 1999).

Material	Solids (%)	pH	C:N ratio	N (%)	Phosphoric acid (%)	Cost ($/ton)[z]
Yard trimming/biosolids (Palm Beach County, Fla.)	70	8	15	2	2.5	20
Yard trimming/biosolids (Nocatee, Fla.)	70	7	23	1.1	2	18
Yard trimming/Food/Biosolids (Disney, Orlando, Fla.)	75	7	25	2.8	5	24
Wood waste/Biosolids (Sarasota, Fla.)	65	7	25	1.8	2.5	18

[z]$1/ton = $ 1.10/t.

Table 3. Pollutant Limits for the use of biosolids in vegetable crop production (U.S. Environmental Protection Agency, 1994 and 1995).

Pollutant	Ceiling concn limits for all biosolids applied to land [$mg \cdot kg^{-1}$ (ppm)][z]	Pollutant concn limits for exceptional quality and pollutant concn biosolids [$mg \cdot kg^{-1}$ (ppm)][z]	Cumulative pollutant loading rate limits (CPLR) biosolids ($kg \cdot ha^{-1}$)[x]	Annual pollutant loading rate limits (APLR) biosolids ($kg \cdot ha^{-1}$/365-d period)[w]
Arsenic	75	41	41	2.0
Cadmium	85	39	39	2.0
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum	75	---	---	---
Nickel	420	420	420	21
Selenium	100	100	100	5.0
Zinc	7,500	2,800	2,800	140
Applies to	All land-applied biosolids	Bulk and bagged biosolids[y]	Bulk biosolids	Bagged biosolids

[z]Dry-weight basis.
[y]Bagged biosolids are sold or given away in a bag or other container.
[x]1 $kg \cdot ha^{-1}$ = 0.9 lb/acre.

Table 4. Pathogen requirements for Class A and B biosolids (U.S. Environmental Protection Agency, 1994).

Classification	Fecal coliform[z]		*Salmonella* sp.[z]
Class A	<1,000 MPN/g total solids	or	<3 MPN/4 g total solids
Class B	<1,000 MPN/g total solids	or	<1,000 cfu/g total solids

[z]MPN = most probably number, cfu = colony forming unit.

pollutant ceiling concentration and pollutant concentration and two loading rates based limit, cumulative pollutant loading rates (CPLR) and annual pollutant loading rates [APLR (Table 3)]. With regard to pathogens density there are two levels of biosolids quality [(Class A and B) Table 4]; and two type of mechanisms to meet vector attraction reduction [processing types or physical barriers to prevent recontamination at the site (USEPA, 1994, 1995)]. If pathogens [*Salmonella* sp., *Escherichia coli*, enteric viruses (viruses which infect cells lining the gastrointestinal tract), and viable helminth ova (parasitic worms such as *Ascaris, Necator, Taenia*, and *Trichuris,* and/or eggs of these worms)] are below detectable levels (Class A), steps were taken to meet vector attraction reduction requirements and meet the pollutant concentration limits for the regulated pollutant elements the biosolids meet the exceptional quality (EQ) biosolids. There are fewer restriction in their use for vegetable production. Biosolids are designated Class B biosolids if pathogens are detectable but have been reduced to levels that do not pose a threat to public health and the environment as long as actions are taken to prevent exposure to the biosolids after their use or disposal. For their use in vegetable production biosolids state regulation, management practices and site restriction are more restrictive than for agronomic crops. These restrictions can limit the use of vegetable receiving biosolids. For example, crops with harvested part that touches the biosolids/soil mixture shall not be harvested for 14 months after application of biosolids. Therefore, most vegetables crops with a short production cycles (less than 150 d), they can not use this type of biosolids. In contrast, if the crop with harvested part that does not touch the biosolids/soil mixture shall not be harvested for 30 d after application of biosolids (plastic beds can be the physical barrier for vector attraction reduction). Therefore, any crops grown in plastics beds can use Class B. The requirements for vegetable crop applications of CPLR and APLR biosolids are more complicated and site specific. Their use is extremely restricted for vegetable crop production. When properly treated and managed in accordance with the existing state and federal regulations and standards, biosolids are safe for the environment and human health (Evanylo, 1999).

Determining biosolids application rate

To determine the amount of biosolids that can be land applied per year, the USEPA recommended the following equation (USEPA, 1994, 1995): annual whole (sludge) biosolids application rate (AWSAR) = APLR/($C \times 0.001$), where APLR is expressed in $kg \cdot ha^{-1}$ per year (Table 3), C is the pollutant concentration per unit biosolids in $mg \cdot kg^{-1}$ dry weight, and 0.001 is a constant.

The biosolids must be analyzed first for the nine regulated pollutant elements. Then using the above calculation, the lowest AWSAR calculated for each pollutant will be the application rate. While this provides an excellent estimate for the amount of biosolids that can be used, normally the limiting factor to the amount of biosolids used is often based on N or agronomic rate, defined as the amount of N needed for the crop to obtain a desired yield while minimizing leaching of N below the root zone to the ground water (Zhang et al., 1998). Biosolids label for container, bag or bulk should contain the total percent N as well as the percent available in the first year. This value can be applied to the amount of biosolids permitted as determined by the AWSAR value. Cumulative pollutant elements are not limiting when biosolids are applied at agronomic rates, because today's biosolids are very clean. For example, if the amount of biosolids is limited by the copper concentration to 20,000

Table 5. Effect of biosolids alone on vegetable crops.[z]

Crop	Biosolids type[y]	Rate (tons/acre)[x]	Soil type	Crop response	Reference
Tomato	Class A, P	0, 4.5, 9, 18	Calcareous	No response	
Squash	Class A, P	0, 1.5, 3, 6	Calcareous	No response	
Bean	Class A, P	0, 1.5, 3, 6	Increased yields		Bryan and Lance, 1991
Cabbage	Class A, P	0, 1.5, 3, 6	Increased yields		
Cauliflower	Class A, P	0, 1.5, 3, 6	Increased yields		
Carrot	Class A	0, 40	Silt loam	Increased yields	Harrison, 1986
Bean	Class A, P	0.7, 1.3	Calcareous	Increased yield	Ozores-Hampton et al., 1994a
Black-eyed pea	Class A, P	0.7, 1.3	Calcareous	Increased yield	Ozores-Hampton et al., 1994a
Tomato	Class A, P	7, 10	Calcareous	Increased yields	Bryan and Lance, 1991
Tomato	Class A, P	0, 7.2	Calcareous	Increased yields	Ozores-Hampton et al., 1994b
Squash	Class A, P	0, 7.2	Calcareous	Increased yields	Ozores-Hampton et al., 1994b
Corn	---[w]	5.8 dry	Various	Increased yields	Shreeg and Jarrett, 1996
Pepper	Class B, C	17	Sandy	Increased yields	Ozores-Hampton et al., 2000

[z]Scientific names: Tomato (*Lycopersicon esculentum*), Squash (*Cucurbita maxima*), Bean (*Phaseolus vulgaris*), Cabbage (*Brassica oleraceae* Capitata), Cauliflower (*Brassica oleraceae* Botrytis), Carrot (*Daucus carota*), Black-eyed pea (*Vigna unguiculata*), Corn (*Zea mays*), Pepper (*Capsicum annuum*).
[y]P = pellets, C = cake.
[x]1 ton/acre = 2.24 $t \cdot ha^{-1}$.
[w]No information.

Table 6. Effect of biosolids combined with other materials on vegetable crops.[z]

Crop	Compost type[y]	Rate (tons/acre)[x]	Soil type	Crop response	Reference
Pepper	CYT/BS	0, 60	Sandy	Increased yields	Smith, 1995
Cucumber	YT/BS	0, 60	Sandy	Increased yields in residual compost	Smith, 1995
Cucumber	YT/BS	0, 60	Sandy	Increased yields	Smith, 1995
Tomato	MSW–BS	0, 6, 12 (year 1)	Sandy	Increased yield with mature compost	Obreza and Reeder, 1994
Watermelon	MSW–BS	0, 6, 12 (year 1)	Sandy	No response to mature compost	Obreza and Reeder, 1994
Tomato	MSW–BS	0, 12, 24 (year 2)	Sandy	Decreased yield with immature compost	Smith, 1995
Watermelon	MSW–BS	0, 12, 24 (year 2)	Sandy	No response to mature compost	Smith, 1995
Tomato	MSW–BS	0, 11	Calcareous	No response to mature compost	Ozores-Hampton et al., 1994b
Squash	MSW–BS	0, 11	Calcareous	No response to mature compost	Ozores-Hampton et al., 1994b
Tomato	MSW–BS	0, 15, 30 (year 1)	Calcareous	Decreased yield 'immature compost'	Bryan et al., 1997
Tomato	MSW–BS	0, 30, 60 (year 2)	Calcareous	Decreased yield immature compost from previous year, but, yield increase with mature compost	Bryan et al., 1997
Cabbage	S/StrC	---[w]	Sandy loam	Increased yield	Smith et al., 1992
Onion	S/StrC	---	Sandy loam	Increased yields	Smith et al., 1992
Corn	SC	0, 18, 36, 72	Sand–gravel	Increased yields	Hornick and Parr, 1987
Bush bean	SC	0, 18, 36, 72	Sand–gravel	Increased yields	Hornick and Parr, 1987

[z]Scientific names: [z]Scientific names: Tomato (*Lycopersicon esculentum*), Squash (*Cucurbita maxima*), Bean (*Phaseolus vulgaris*), Bush bean (*Phaseolus vulgaris*), Cabbage (*Brassica oleraceae* Capitata), Cauliflower (*Brassica oleraceae* Botrytis), Carrot (*Daucus carota*), Black-eyed pea (*Vigna unguiculata*), Corn (*Zea mays*), Pepper (*Capsicum annuum*), Cucumber (*Cucumis sativus*), Watermelon (*Citrullus vulgaris*), Onion (*Allium cepa*).
[y]YT = yard trimmings, BS = biosolids, MSW = municipal solid waste,S/StrC = sludge/straw compost, SC = sludge compost.
[x]1 ton/acre = 2.24 $t \cdot ha^{-1}$.
[w]No information.

lb/acre (24,000 $kg \cdot ha^{-1}$) and the biosolids contain 2% total N and 50% mineralization in the first year, then the maximum amount of N that can be applied is 200 lb/acre [(240 $kg \cdot ha^{-1}$) Zhang et al., 1998]. There are several factor affecting the agronomic rate such as: total and available N of the biosolids, N losses, other sources of N, and expected yields. This amount may exceed the maximum value for the crop however, so this must also be considered when applying biosolids to vegetable production.

Biosolids prices

Most biosolids originate from the same feedstock, but can differ in physical form according to the amount of dewatering they undergo before they are land-applied. In general, the more processing (stabilization) a biosolids material undergoes before it leaves the wastewater treatment plant, the more costly it is. Hence, dried biosolids are more costly than slurries or cakes (Table 1).

Effect of biosolids on vegetables production

Application of biosolids alone or in combination with other materials to soils was reported to increase yields of several vegetable crops including tomatoes (*Lycopersicon esculentum*), squash (*Cucurbita maxima*), and beans (*Phaseolus vulgaris*) (Tables 5 and 6). In Florida, application rates as low as 3 to 6 tons/acre (6.7 to 13.5 $t \cdot ha^{-1}$) resulted in crop yield increases for tomatoes, squash, and beans (Bryan and

Lance, 1991; Ozores-Hampton et al., 1994a, 1994b). Biosolids reduced N fertilizer requirements by 50% to attain marketable peppers (*Capsicum annuum*) yields equal to those attain with recommended fertilizer (Ozores et al., 2000). Plant biomass was higher in the biosolids treatment compared with the control treatment with biosolids application. Soil pH and Mehlich 1-extractable phosphorus, potassium, calcium, magnesium, zinc, manganese, iron, and copper were higher in biosolids-treated plots than in control plots. Soil organic matter concentration was 3-fold higher where biosolids were applied compared to non-amended soil.

Combining biosolids and inorganic fertilizer has generally been more effective in producing a positive plant response than separate application of either material alone (Ozores-Hampton et al., 1999, 2000).

There are several benefits to growers through the use of biosolids: improving soil physical (water holding capacity), chemical (reduce fertilizer application) and biological properties such as increasing microbial communities (Gallardo-Lara and Nogales, 1987; Li et al., 2000).

There are two problems confronting the use of biosolids in today's industries. The rising production cost is one of the major concerns. The second, is the stigma attached to using biosolids by the public. This includes public fears that land application of biosolids will lead to environmental degradation, including soil contamination, groundwater pollution, and potential threat to human and animal health due to the presence of pathogens (Li et al., 2000; Muchovej and Obreza, 1999). It should be noted that USEPA has strict guidelines regulating the production and use of biosolids in the U.S. These regulations are based on scientific studies in the effects of biosolids on soil–plant-animal–human interaction. There have been no negative human health impacts documented when biosolids meet the federal regulations and have been applied to land under best management practices (USEPA, 1999).

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