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Effects of Sewage Sludge on Soil Physical, Chemical and Biological Properties

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Abstract

Sewage sludge, also known as biosolids, is the insoluble residue generated during the treatment of domestic sewage and industrial wastewater, and its land application has become a common and economical disposal method. This paper reviews the effects of sewage sludge on soil physical and chemical properties as well as potential environmental risks. Sewage sludge is rich in organic matter, macronutrients and micronutrients, but its nutrient content varies with sources and treatment processes, and heavy metal concentrations show significant regional differences. The application of sewage sludge can reduce soil bulk density, increase porosity, improve water-holding capacity and infiltration rate, while enhancing soil organic matter content and nutrient levels, thereby improving soil physical and chemical properties. However, long-term or excessive application may lead to the accumulation of heavy metals and nitrate in soil, increasing the risks of groundwater pollution and adverse impacts on human health. Additionally, there are controversies in existing studies regarding the effect of sewage sludge application on soil aggregate stability. Therefore, prior to the land application of sewage sludge, a comprehensive assessment of sludge characteristics, soil types and crop species is necessary to balance its resource utilization and environmental safety.

Keywords

Sewage Sludge; Soil Physical Properties; Soil Chemical Properties; Heavy Metals; Environmental Risks; Land Application.

1. Introduction

Sewage sludge, also referred to as biosolids, is the insoluble residue generated during the treatment of domestic sewage and industrial wastewater. Approximately 6.2 million dry metric tons of sludge is produced each year in the United States and continues to increase because of growing urbanization . These amounts are overburdening the landfills. Fortunately, agriculture realizes the benefits of sewage sludge as an organic amendment to improve soil properties and to provide nutrients for crop growth. Application of sewage sludge to cropland has become a common and inexpensive option of disposal over the past several decades.

Therefore, the objective of this term paper is to briefly review the effects of sewage sludge on soil physical and chemical properties.

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2. Discussion

2.1. Nutrient Content in Sewage Sludge

The main components of sewage sludge are organic matter, macronutrients, a wide range of micronutrients and certain types of heavy metal from the industrial effluents. Analysis of different sewage sludge samples collected over two years from eight cities of Indiana, U.S. showed that sewage sludge contained approximately 50% organic matter and 1- 4% inorganic carbon[1]. According to some research, total N and P content in sewage sludge is higher while total K, Ca and Mg content is lower than dairy and beef manure; poultry litter has the highest nutrient levels (table 1).

Table 1. Nutrient concentration in sewage sludge and selected animal manures

Organic Wastes		N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Sewage sludge1		1.88	0.62	0.17	0.88	0.11
Animal manure2	Dairy	0.61	0.17	0.50	1.54	0.36
	Beef	0.73	0.23	0.57	1.50	0.41
	Poultry	2.37	1.11	1.17	4.60	2.28

Note: 1. Balkcom et al., 2001[2] ;2. Ministry of agriculture, food and rural affairs, Canada

Table 2. Comparison of sewage sludge from different countries

Properties	Thailand	Spain	India
pH	6.82	8.6	7.1
Organic matter (%)	19.82	43.4	23.2
Total N (%)	3.43	2.5	2.6
Total P (%)	1.62	1.36	1.34
Cu (mg/kg)	801	174	700
Zn (mg/kg)	1326	445	1900
Mn (mg/kg)	2621	--	400

(Adapted from Singh et al., 2008[3])

Characteristics of sewage sludge vary due to different wastewater treatment processes before application. Concentrations of organic and inorganic C, organic N and inorganic P, Ca and Mg were relatively constant in different sewage sludges but inorganic N, organic P, K were quite variable[1]. Singh et al.[3]compared sewage sludge from different countries and clearly showed that pH varied from an acidic to an alkaline range. Organic matter content and some heavy metals (Cu, Zn and Mn) also varied considerably yet there was no significant variation on total N and P contents (table 2).

2.2. Effects of Sewage Sludge on soil Physical and Chemical Properties

A large number of studies have been done to determine the effects of sewage sludge application on soil properties.

2.2.1. Soil Physical Properties

Application of composted sewage sludge could improve the soil physical properties [4]. Addition of sewage sludge could lower the bulk density, increase porosity, water holding capacity and infiltration rate [5-7]. A simulation study conducted to determine the effect of sewage sludge application on soil properties indicated that sludge addition in soil could significantly improved the soil hydraulic conductivity after 27 days of incubation. Addition of sewage sludge could also improve soil aggregate stability[6]. Epstein[7] reported that after 175

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days of incubation with 0.5% sewage sludge, the average percentage of stable aggregates was 34%, two-fold higher than the untreated soil. However, Debosz et al. [8] showed different results. This 3-year field experiment indicated there were no accumulated effects of waste amendment on soil wet-stable aggregates. Therefore further studies needed to be done to verify whether application of sewage sludge affects soil aggregation.

2.2.2. Soil Chemical Properties

Generally, addition of sewage could improve soil fertility. An experiment conducted in California, U.S. over two years showed that a cumulative total of 74 dry Mt/ha of sewage sludge compost had the positive effects of increasing organic matter from 0.77% to 1.50%, and increasing the levels of the primary plant nutrients (table 3). However, it also increased soluble salts from 1.52 to 2.44 dS/m, which was a negative effect for crop growth (Bevacqual and Mellama, 1993).

Table 3. Soil properties after two years application of sewage sludge compost

Cumulative sludge Compost (Dry Mt/ha)	OM (%)	EC (dS/m)	NH4-N (ppm)	NO3-N (ppm)	P (ppm)	K (ppm)
0	0.77 a	1.52 a	4.8 a	4.5 a	13 a	311 a
37	1.00 b	1.48 a	6.5 b	6.6 a	27 b	314 b
74	1.50 c	2.44 b	6.0 b	11.7 b	50 c	358 b

(Adapted from Bevacqual and Mellama, 1993[9])

Magdoff and Amadon [10] conducted both laboratory and field experiments to evaluate the nitrogen contribution of the sewage sludge to crops. They found that mineralization of organic N from sludge averaged 55% under field conditions during the first year of application. Another field experiment showed that mineral N and resin-extractable P were increased by 1.8-fold and 1.6-fold respectively after 3 years application of composted sewage sludge[8]. Balkcom et al.[2] conducted a field research using resin bags and PVC cores to determine the release and leaching of selected nutrients from municipal sludge compost. They found mineralization of selected elements occurred only 2 weeks after application. Concentrations of four elements were increased after 1 year: Ca was the greatest at 16 mg/kg, followed by P, Mg and Zn at 11, 2 and 0.8 mg/kg, respectively. These studies showed that the total nutrients released from the sewage sludge were inadequate for crop growth, indicating it is necessary to apply sludge at large rates.

Changes of soil pH are also important because some toxic heavy metals are generally more available to plants at lower pH levels. Veeresh et al.[5]reported that sewage sludge applied at 52 t/ha significantly reduced pH of three types of soils in India, for example, from 8.6 to 8.2 in vertisol. Increased soil pH after sewage sludge treatment was also reported [11]. Sommers[12] related changes in soil pH to the calcium carbonate content of sludges and the acid production during sludge decomposition.

2.2.3. Soil Biological Properties

Soil biological components-including microorganisms (bacteria, actinomycetes, fungi, algae), macrofauna (earthworms, microarthropods), and plants-play pivotal roles in organic waste decomposition, nutrient cycling (N, P, S), and soil fertility maintenance. However, research on the effects of sewage sludge organic matter (SSOM) on these components, whether beneficial or detrimental, remains relatively scarce, and its impacts are often intertwined with soil physical and chemical changes. This abstract synthesizes key findings from multiple regional studies to clarify SSOM's biological influences.

SSOM consistently alters microbial communities across soil types. In a study of three distinct Ohio soils, SSOM application increased bacterial and actinomycete counts in direct proportion

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to sludge loading rates, with peak populations observed 1 month post-incubation (then declining at 3 and 6 months); fungal populations rose too but less markedly. Notably, 354 bacterial isolates from anaerobically digested sludge-treated soils showed community shifts-gram-negative bacteria accounted for ≥50% of isolates, versus gram-positive dominance in controls-along with physiological changes (faster growth rates, better survival at 5°C but poorer at 35°C, higher NaCl tolerance) and biochemical traits (elevated catalase/cytochrome oxidase activity, enhanced citrate utilization, reduced starch hydrolysis, and greater antibiotic resistance). An Illinois 6-year experiment on silt loam soil (up to 370 Mg/ha SSOM) found no evidence of microbial suppression: total bacterial/fungal/actinomycete counts never fell below controls, denitrifier percentages and protease/amylase activities increased, though significant population boosts occurred only once across three samplings. Swiss 5-year trials on sandy loam soil showed SSOM elevated heterotrophic microbes (aerobic bacteria, actinomycetes, yeasts, hyphal fungi) and mineralization processes (respiration, ammonification), while reducing autotrophic algae; grassland soils saw stronger microbial responses than arable soils. Italian studies noted that composted SSOM primarily affected microbial activity (not abundance) and that rhizosphere microbial growth (bacteria, fungi, actinomycetes) and functions (nitrification, enzyme activity) depended on sludge dosage.

Earthworms (Eisenia foetida) drive SSOM decomposition-New York microcosm studies found they accelerated sludge stabilization, mixed sludge with soil, converted labile sludge components to biomass/respiration, and reduced odors/pathogens, with earthworm biomass increasing only in sludge-amended soils. However, another New York study warned earthworms accumulate Cd, posing health risks via garden soil contamination or bird predation. Additionally, field research showed SSOM reduced microarthropod populations (collembola, mites) in 4/5 tested genera versus fertilized/unfertilized controls, likely due to toxic anaerobic decomposition products (toxicity faded post-soil incorporation).

Fresh SSOM inhibits seed germination (via ammonia, salts, ethylene oxide), but effects are short-lived (days) and dosage-dependent; delayed planting or pre-application sludge storage mitigates inhibition, and field studies show no germination differences versus controls. SSOM also improves root growth-reducing penetration resistance and boosting root-shoot ratios versus inorganic fertilizer treatments-and aids non-agricultural uses: it reclaims mine spoils, revegetates highway banks/dredged sediments, and fertilizes forests (80 Mg DM/ha every 5–10 years, effective on 30% slopes). While SSOM increases yields of five crops (e.g., via enhanced soil moisture and slow N/P release), wheat grain yield showed no improvement in one light calcareous loam study.

2.3. Potential Environmental Risks

The fertilizer value of sewage sludge has been known for a very long time, but the recognition of related problems is relatively recent. The major concern about sewage sludge applied to cropland is the accumulation of potentially toxic elements due to long-term uses [13]. Once accumulated, heavy metals are highly persistent in the topsoil and may pose a high risk to human health.

After more than 20-year application of dewatered sewage sludge at 244 t/ha, Kelly et al. [14]reported that the amounts of total and soluble metals were significantly higher for the sludge treatment, including a 100-fold increase in soluble cadmium, and greater than 20-fold increases in soluble zinc and copper (table 4).

The toxicity of heavy metals derived from sewage sludge depends on various factors such as nature and the amount of heavy metals, soil properties and climates[15]. For example, Cd is regarded as the most hazardous metal element. Increase in the dietary uptake of Cd is a potential risk to human health associated with the land application of sewage sludge.

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Table 4. Heavy metal concentration in sludge treated soil

Treatments		Cd	Cr	Cu	Ni	Pb	Zn
		----------------- Total metal (mg/kg) --------------------					
Control		12.5	39.8	23.4	33.4	133	123
Sludge		44.5	512	341	159	337	1506
		----------------- Soluble metal (mg/kg) -----------------					
Control		0.012	ND	0.066	ND	0.034	0.083
Sludge		1.172	ND	1.515	ND	0.159	1.966

(Adapted from Kelly et al., 1999[14])

Repeatedly or excessively application of sewage sludge could also result in the accumulation of nitrate in the topsoil and consequently nitrate pollution. Stamatiadis et al. [16]found that only after two weeks 72% of the ammonium in liquid sewage sludge was converted to nitrate, whose concentration was raised to a level of 50 ppm, two times higher than sufficient level for corn during early growing season. Ground water nitrate concentration also increased by 9 ppm after they applied a cumulative amount of 52 Mg/ha of dry solids over 12-years periods. Such high soil nitrate levels could pose a serious risk for groundwater contamination and human health.

3. Summary

Application of sewage sludge to cropland could provide essential nutrients for plant growth and improve soil physical and chemical properties. However, as the bioavailability of heavy metals and nitrate in sewage sludge increase with its long-term use, characteristics of soil types and sewage sludge as well as plant species to be grown need to be carefully assessed prior to land application of sewage sludge.

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