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Soil application of sewage sludge stabilized with steelmaking slag and its effect on soil properties and wheat growth

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ABSTRACT

The effect of sewage sludge, stabilized with steelmaking slag, on soil chemical properties and fertility and on wheat (*Triticum aestivum* L.) growth was evaluated. Dewatered sewage sludge [75% (wet weight basis)] stabilized with steelmaking slag (25%) and three soils with different pH values were used in a pot experiment with winter wheat. The following treatments were applied: (i) sludge addition of 30 g kg^{-1} (≈ 120 Mg ha^{-1}, rate equivalent to the common inorganic N fertilization for wheat, based on sludge's water soluble NO_3-N), (ii) sludge addition of 10 g kg^{-1} (≈ 40 Mg ha^{-1}, rate equivalent to the common inorganic N fertilization for wheat, based on sludge's Kjeldahl-N), (iii) addition of the common inorganic N fertilization for wheat (120 kg N ha^{-1}) as NH_4NO_3, (iv) control (no fertilizer, no sludge). Sludge application at both rates to all soils resulted in a significant increase of pH, electrical conductivity of the saturation extract (EC_{se}) and soil available NO_3-N and P, in comparison to the other two treatments and this increase remained constant till the end of the pot experiment. In sludge treatments pH did not exceed the critical value of 8.5, whereas EC_{se}, although it did not reach the limit of 4 dS m^{-1}, exceeded the value of 2 dS m^{-1} at the rate of 30 g kg^{-1}. Concentrations of heavy metals, which regulate the agronomic use of sewage sludge according to the established legislation, ranged from not detectable to lower than the respective permissible levels. Both rates of sludge's addition in all soils improved wheat's growth, as judged by the significant increase of the aboveground biomass yield and the total plant uptake of almost all nutrients, compared to the other two treatments. It was concluded that sewage sludge stabilized with steelmaking slag could be used in agriculture, applied at rates based on sludge's Kjeldahl-N content and crop's demand for N. However, potential environmental impacts must also be considered.

1. Introduction

Sewage sludge according to the Greek and European legislation must be stabilized before being used in agriculture. Some of the stabilization processes include aerobic and anaerobic digestion, composting and chemical treatment. In the chemical treatment, the most common method for effective sludge stabilization is the addition of hydrated lime [$Ca(OH)_2$], at a concentration sufficient to raise sludge's pH above 12 for a minimum period of two hours (lime stabilization) (Fytili and Zabaniotou, 2008). There are several materials that have been and could be used for alkaline stabilization of sewage sludge, such as cement kiln dust, lime kiln dust, hydrated lime, quick lime (CaO), limestone, alkaline fly ash, other coal burning ashes, wood ash and steelmaking slag (Logan and Harrison, 1995; Papastergiadis et al., 2015; Su and Wong, 2002; Wysokinski and Kalembasa, 2009; Zhang et al., 2016).

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Steelmaking slag is a by-product of the steel refining process. It is an inorganic material with a high content of alkaline constituents (e.g. 29% Ca and 5% Mg, other main constituents being Si, Fe, Al and Mn). It also contains heavy metals (e.g. Cd, Cu, Ni, Pb, Zn, Cr), some of which are essential for plant growth (Besga et al., 1997). Because of its high alkalinity, steelmaking slag can be used as a liming material for acid soils (Besga et al., 1997; Capuani et al., 2015). Besga et al. (1997) found that slag addition to pasture soils decreased exchangeable Al and thus increased their pH and also enhanced Ca and Mg and decreased Mn concentrations in herbage. Moreover, Capuani et al. (2015) reported that slag was more efficient than limestone in improving the properties of an acid soil, like pH, sum of bases, percentage of base saturation and cation exchange capacity (CEC).

Furthermore, because of its chemical composition and high pH, steelmaking slag was tested successfully as a material for the stabilization of sewage sludge (Papastergiadis et al., 2015; Zhang et al., 2016). Papastergiadis et al. (2015) reported that addition of steelmaking slag to sewage sludge at a rate of 20% resulted in a stabilized sludge product with high alkaline pH value, low content of moisture and volatiles and not detectable microbial load. In addition, Zhang et al. (2016) concluded that slag can be used as a substitute for NaOH in sewage sludge alkaline treatment.

The agronomic use of sewage sludge has beneficial effects on crops' yield due to the enhancement of soil fertility in terms of macronutrients, especially N (Akdeniz et al., 2006; Antoniadis et al., 2015) and P (Bueno et al., 2011; Hagreaves et al., 2008); although improvement of soil fertility with respect to micronutrients cannot also be ignored. Additionally it can enhance soil fertility through the increase of organic matter (Bueno et al., 2011; Carbonell et al., 2011; Castro et al., 2009; Samaras et al., 2008).

Certain risks that may arise from the agronomic use of sewage sludge are soil salinization, and NO_3^- loss into the deeper soil layers (Mantovi et al., 2005; Samaras et al., 2008). Because of the physical-chemical treatment of the wastewater, sludge tends to accumulate heavy metals existing in the wastewater. Metal concentrations in sewage sludge may vary widely depending on sludge's origin. The potential build up of heavy metals in soils raises concerns about various environmental risks. However, these risks depend on sludge's composition and are usually associated with heavy application rates of sewage sludge to soils (Clapp et al., 1994; De Brouwere and Smolders, 2006; Fytili and Zabaniotou, 2008).

The agronomic use of sewage sludge in the European Union is regulated by the 86/278/EEC Directive. The Greek legislation (KYA 80568/4225/91) is in accordance with the aforementioned European Directive. According to both legislations, the permissible levels of heavy metals concentrations in sludge and soil to which sludge is going to be applied and of the maximum annual quantities of heavy metals which can be introduced into agricultural soils are given in Table 1.

In view of the above, sewage sludge stabilized with steelmaking slag was applied to three soils at two rates equivalent to the common inorganic fertilization for wheat (based on its Kjeldahl-N or NO_3-N content) and the objectives of this study were to evaluate its effect on: (a) soil chemical properties and fertility and (b) certain agronomic characteristics of wheat.

Table 1
Critical levels of heavy metals in sewage sludge and soil and their permissible amounts that can be added to soil in the form of sludge, according to the Greek and European legislation.

Element	Sewage sludge	Soil	In the form of sludge
	(mg kg^{-1} of dry weight)		(kg^{-1} ha^{-1} yr^{-1})
Cd	20–40	1–3	0.15
Cu	1000–1750	50–140	12
Ni	300–400	30–75	3
Pb	750–1200	50–300	15
Zn	2500–4000	150–300	30
Hg	16–25	1–1.5	0.1
Cr	–	–	–

2. Materials and methods

2.1. Soils

Soil surface-samples (0–20 cm) were collected from several locations of northern Greece, in order to select soils for the experiment. The soil samples, after air drying and passing through a 2-mm sieve, were analyzed for the following properties in duplicate. Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962), pH was measured in a 1:2 suspension with water and available NO_3-N and NH_4-N were extracted with 2 M KCl and determined by ultraviolet spectrometry and the sodium salicylate - sodium nitroprusside method, respectively (Mulvaney, 1996). In addition, the presence of free $CaCO_3$ was detected in the alkaline soils by reaction with 4 M HCl. Three soils that differed in their pH and had relatively low available NO_3-N content were chosen to be used in the present study.

An adequate quantity of the three soils, designated as Soil 1, Soil 2 and Soil 3, was collected. The soil samples were air-dried and passed through a 6.35-mm sieve and this material was used in the pot experiment. Part of this material passed through a 2-mm sieve and was analyzed for the aforementioned and the following properties in duplicate (Table 2). Organic C was determined by the wet oxidation method (Walkley and Black, 1934) and CEC was determined using 1 M CH_3COONa, pH 7, as saturating solution and 1 M CH_3COONH_4, pH 7, as replacing solution (Chapman, 1965). Soil available P was extracted with 0.5 M $NaHCO_3$, pH 8.5 and determined by the molybdenum blue-ascorbic acid method (Kuo, 1996) and K was extracted with 1 M CH_3COONH_4, pH 7 and determined by flame photometry (Thomas, 1982). Soil available Cu, Zn, Fe and Mn were extracted with DTPA (Lindsay and Norvell, 1978) and determined by atomic absorption spectrometry and B was extracted with hot water and determined by the azomethine-H method (Keren, 1996). In addition, in Soil 3, which was alkaline

Table 2
Certain physicochemical properties of the three soils and concentrations of available nutrients.

Soils	Clay (g kg^{-1})	pH (1:2 H_2O)	Organic C (g kg^{-1})	CEC (cmol$_c$ kg^{-1})
1	109[a] ± 7[b]	5.4 ± 0.0	9.1 ± 0.1	10.1 ± 1.0
2	170 ± 14	7.2 ± 0.0	5.5 ± 0.9	18.4 ± 1.0
3	200 ± 0	7.9 ± 0.1	5.8 ± 0.5	15.0 ± 1.6
	NO_3-N	NH_4-N	P	K
	(mg kg^{-1})			
1	12.9 ± 0.6	19.7 ± 1.4	10.4 ± 0.3	57.2 ± 1.4
2	10.1 ± 0.9	11.3 ± 0.8	17.1 ± 2.9	84.8 ± 5.8
3	20.0 ± 0.6	10.9 ± 0.9	26.3 ± 3.5	133.3 ± 4.0

Soils	Cu	Zn	Fe	Mn	B
	(mg kg^{-1})				
1	0.87 ± 0.15	1.49 ± 0.12	56.7 ± 6.9	52.1 ± 2.8	0.25 ± 0.01
2	1.66 ± 0.22	1.42 ± 0.15	21.8 ± 1.2	14.4 ± 1.1	0.50 ± 0.01
3	1.80 ± 0.16	1.02 ± 0.24	17.1 ± 0.4	11.5 ± 0.7	0.48 ± 0.06

[a] Mean.
[b] Standard deviation.

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