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Application of biochar to sewage sludge reduces toxicity and improve organisms growth in sewage sludge-amended soil in long term field experiment

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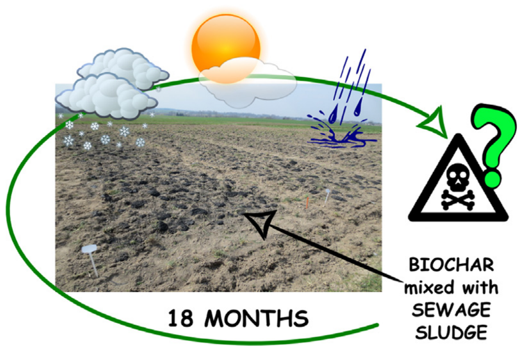
HIGHLIGHTS

- Impact of co-application of biochar with sewage sludge to soil on toxicity was investigated.
- Application of biochar to sewage sludge increased the immobilization of nutrients in soil.
- Application of biochar to sewage sludge reduced toxicity of sludge-amended soil.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the present study was to determine changes in the physicochemical properties and toxicity of soil amended with sewage sludge (10 t_{dw}/ha) or sewage sludge (10 t_{dw}/ha) with biochar addition (2.5, 5 or 10% of sewage sludge). The study was carried out as a field experiment over a period of 18 months. Samples for analysis were taken at the beginning of the experiment as well as after 6, 12 and 18 months. The study investigated toxicity of the unamended soil, sewage sludge-amended soil and sewage sludge-amended soil with biochar addition towards *Folsomia candida* (collembolan test) and *Lepidium sativum* (Phytotoxkit F). Moreover, toxicity of aqueous extracts obtained from the tested soils towards *Vibrio fischeri* (Microtox®) and *Lepidium sativum* (elongation test) was determined.

The study showed that addition of biochar to the sewage sludge and soil reduced leaching of nutrients (mainly phosphorus and potassium) from the amended soil. Biochar significantly reduced sewage sludge toxicity, exhibiting a stimulating effect on the tested organisms. The stimulating effect of biochar addition to the sewage sludge persisted throughout the entire experiment. Apart from the remediatory character of biochar, this is also evidence of its fertilizing character. In the tests with *L. sativum* (leachates and solid phase) and *V. fischeri* (leachates), increasing the rate of biochar in the sewage sludge increased root growth stimulation (*L. sativum*) and bacteria luminescence (*V. fischeri*). However, increasing biochar rate decreased *F. candida* reproduction stimulation, which could have been an effect of reduced nutrient bioavailability due to the biochar.

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1. Introduction

Sewage sludge is a waste that contains a high content of organic matter, phosphorus, nitrogen and microelements, so the preferred method for its management is the environmental usage. (Bravo-Martín-Consuegra et al., 2015). But such usage of sewage sludge creates a risk associated with the presence of harmful substances (heavy metals, polycyclic aromatic hydrocarbons or polychlorinated biphenyls) in sewage sludge (Oleszczuk and Hollert, 2011). Depending on the application rate of sewage sludge and the level of its contamination, the soil can become contaminated when sewage sludge is applied. As a result, new solutions are being sought to exploit the advantages of sewage sludge and reduce the environmental risks associated with its use.

One of the new directions of agricultural management of sewage sludge is its use as a fertilizer in combination with carbon adsorbents (e.g. activated carbon or biochar) (Frišták and Soja, 2015; Oleszczuk et al., 2012a; Stefaniuk and Oleszczuk, 2016). This win-win solution allows to utilize sewage sludge rich in organic matter and nutrients (Suciu et al., 2015) and, at the same time, reduce the mobility of contaminants due to their being bound by a carbon absorbent (Frišták and Soja, 2015; Oleszczuk et al., 2012a, 2014). The benefits arising from the properties of biochar are an additional advantage of sewage sludge application in combination with biochar. Biochar has good fertilizing properties and, likewise sewage sludge, may beneficially affect the physical, chemical and biological properties of soils (Glaser et al., 2002).

Recent research has revealed that adding carbon adsorbents such as activated carbon (AC) or biochar to sewage sludge allows immobilization of the bioavailable fraction of polycyclic aromatic hydrocarbons (PAHs) (Oleszczuk et al., 2012a, 2014; Stefaniuk and Oleszczuk, 2016) and heavy metals (cadmium, copper, lead, zinc) (Frišták and Soja, 2015; Gwenzi et al., 2016). Our recent study also demonstrated (Stefaniuk et al., 2017) that despite of the PAHs immobilization in sewage sludge amended soil, biodegradation of PAHs occurs after usage of biochar. This is particularly beneficial because, contrary to appearances, after biochar application the persistence of PAHs in sewage sludge-amended soil does not increase. The studies of other authors (Frišták and Soja, 2015) also show that biochar application in combination with sewage sludge used as a soil amendment allowed the content of available forms of phosphorus to be increased and the amount of nutrients leached to be reduced, thus contributing to reduced risk of eutrophication of water bodies (Frišták and Soja, 2015). Based on the above, it can be expected that co-application of sewage sludge with biochar may lead to a reduction in environmental risk (decreased toxicity of the sewage sludge applied) associated with the effects of various groups of contaminants.

Existing research, mainly laboratory studies, has shown that adding biochar to sewage sludge may positively affect the growth of *Lepidium sativum* (Oleszczuk et al., 2012b; Stefaniuk and Oleszczuk, 2016) as well as the growth and number of leaves of *Zea mays* (Gwenzi et al., 2016), and may stimulate the reproduction of *Folsomia candida* and luminescence of *Vibrio fischeri* bacteria (Stefaniuk and Oleszczuk, 2016). It should be stressed that existing studies were conducted at the laboratory scale (Oleszczuk et al., 2012b; Stefaniuk and Oleszczuk, 2016) or they covered a short period of time (14–49 days) (Frišták and Soja, 2015; Gwenzi et al., 2016). Under such conditions, external factors, such as changes in seasons, agricultural practices, etc., are not taken into account. Also, too short studies do not allow the long-term effects of co-application of biochar and sewage sludge to be identified.

The aim of this study was to determine, under a long-term field experiment, the effect of biochar on the toxicity of sewage sludge-amended soil towards organisms representing various trophic groups: plants (*Lepidium sativum*), bacteria (*Vibrio fischeri*), and arthropods (*Folsomia candida*). The leachates obtained from the soil tested were also evaluated.

2. Materials and methods

2.1. Field experiment

A field experiment was located at the Bezek Farm (Poland) (N: 50°20′04″ E: 23°29′49″). The experiment was set up in 3 plots (18.5 m^2 each) on podzolic soil (S) with the granulometric composition of loamy sand (Table 1). Sewage sludge (SL) produced in municipal sewage treatment plant (localized in Chełm) and biochar (BC) produced from willow (*Salix viminalis*) and provided by Mostostal SA (Wrocław, Poland) were added to the soil as fertilizers. Sewage treatment plants used mainly urban wastewater without the great impact of the industry. Sewage sludge was hygienic stabilized (biologically – aerobic fermentation and chemically – threated with lime) and then dried in a glasshouse automatic dryer (solar dryer). BC was obtained by slow pyrolysis at a temperature 700 °C.

SL with or without BC were added before sowing during spring tillage operations. Sewage sludge and biochar (in suitable doses) were mixed together by mechanical (concrete) mixer, added to soil and next precisely mixed with soil by the rotatory tiller (operating depth – 22 ± 2 cm, width - 185 cm). The experiment was prepared in the following scheme: (1) control soil without amendments and fertilization (S); (2) sewage sludge (10 t_{dw}/ha) and soil (S + SL); (3) sewage sludge with biochar (2.5%) and with soil (S + SL + 2.5% BC); (4) sewage sludge with biochar (5%) and with soil (S + SL + 5% BC) and (5) sewage sludge with biochar (10%) and with soil (S + SL + 10% BC).

2.2. Samples collection

Samples of soil were collected in four terms (0, 6, 12 and 18 months after the application of sewage sludge or sewage sludge with biochar to soil). Samples were taken according to the ISO guideline 10,381 (ISO, 2002). From each plot 10 sub-samples were taken from 25-cm layer of soil using a stainless steel corer (2 cm in diameter). All sub-samples from particular plot were mixed together to obtain a representative sample. All samples were air-dried in air-conditioned storage rooms (20–25 °C), manually crushed and sieved (<2 mm) prior to chemical and ecotoxicological analysis. Additional information about field experimental conditions such as climatic conditions and historical information are presented in Supplementary data.

2.3. Physico-chemical properties

The physico-chemical properties of samples (biochar, sewage sludge, soil, soil amended with sewage sludge and soil amended with sewage sludge and biochar) were determined by standard methods. The pH and EC of the suspensions (1 g mixture/10 mL of deionized water) was measured using a digital pH and EC meter HQ430d Benchtop Single Input (HACH, USA). Available phosphorus (P), magnesium (Mg) and potassium (K), or total content nitrogen were determined according to procedures for soil analysis (Van Reeuwijk, 1995). Total forms of cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) were determined by Pallman methods in 1 M NH_4Cl [10]. Dissolved organic carbon (DOC), total organic carbon (TOC) was determined by TOC-VCSH (SHIMADZU). The metal content in soil, sewage sludge and biochar were determined using a START D microwave oven (Milestone, Italy) via a wet method in a mixture of nitric acid (8 mL) and hydrochloric acid (2 mL) at a ratio of 4:1. Analysis of the Cr, Cu, Ni, Pb, Cd, Zn and Co contents was carried out using ICP-OES (Thermo Scientific, ICAP 7000 Series, USA). Information about additional analysis of biochar and contaminants content are presented in Supporting information.

2.4. Samples toxicity

All samples were evaluated by two solid phase tests. To evaluate samples toxicity to springtails, the test was carried out with *Folsomia*