



The effect of sewage sludge application on soil properties and willow (*Salix* sp.) cultivation



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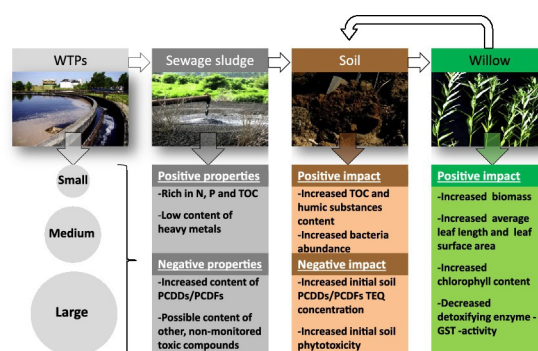
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HIGHLIGHTS

- The sludge meets the legislation criteria, and can be used as fertilizer for soil and plants.
- The sludge had positive effect on the soil properties.
- The initial increase in soil phytotoxicity and PCDDs/Fs TEQ was ameliorated by willow cultivation.
- Sludge application had positive effect on the willow growth and metabolism.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the study was to determine the impact of sewage sludge from three wastewater treatment plants of different sizes (small, medium and large) applied in two doses (3 and 9 tons per hectare) on soil properties, determined as the content of organic carbon and humus fractions, bacterial abundance, phytotoxicity and PCDD/PCDF TEQ concentrations. The study also evaluated the impact of this sewage sludge on the biometric and physiological parameters and detoxification reaction of willow (*Salix* sp.) as a typical crop used for the remediation of soil following sludge application.

The cultivation of willow on soil treated with sludge was found to result in a gradual increase of humus fractions, total organic carbon content and bacterial abundance as well as soil properties measured using *Lepidium sativum*. However, it also produced an initial increase of soil phytotoxicity, indicated by *Sinapis alba* and *Sorghum saccharatum*, and PCDD/PCDF Toxic Equivalent (TEQ) concentrations, which then fell during the course of the experiment, particularly in areas planted by willow.

Although the soil phytotoxicity and PCDD/PCDF TEQ content of the sewage sludge-amended soil initially increased, sludge application was found to have a positive influence on willow, probably due to its high nutrient and carbon content. The obtained results reveal increases in willow biomass, average leaf surface area and leaf length as well as chlorophyll *a + b* content. Moreover, a strong decline was found in the activity of the detoxifying enzyme glutathione S-transferase (GSTs), a multifunctional enzyme involved in the metabolism of xenobiotics in plants, again demonstrating the used sludge had a positive influence on willow performance.

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1. Introduction

Rapid growth has been observed in global population, from approximately 5.3 billion in 1992 to about 7.4 billion in 2016 (World Population Data Sheet, 2016) and according to United Nation projections, global population will reach over eight billion in 2030 and nine billion in 2050. One effect of such rapid population growth is an increasing consumption of global water and consequential production of wastewater, as well as sewage sludge, which accounts for 0.3 to 0.5% of the amount of treated wastewater (Li et al., 2011).

The quantities of treated wastewater, and thus the amount of sewage sludge produced, are also growing throughout the EU as a result of the progressive implementation of the Urban Waste Water Treatment Directive 91/271/EEC. From an annual production of some 5.5 million tons (t) of dry matter in 1992, the Community was approaching nearly 9 million t by the end of 2005. Among the new EU members (EU-12), Poland has been the greatest sludge producer, producing almost 42% of total EU sludge (Kelessidis and Stasinakis, 2012), with more than a 50% increase of production over the last 15 years.

Such significant intensification of sewage sludge production demands specific methods of utilization and disposal. Together with valuable nutrients such as nitrogen and phosphorus, sludge also contains heavy metals whose levels in soil are defined at national and European levels, as well as a wide range of non-monitored toxic organic compounds, such as polycyclic aromatic hydrocarbons (PAHs) (Oleszczuk, 2006; Oleszczuk and Hollert, 2011; Oleszczuk et al., 2012), pharmaceuticals (Jelic et al., 2011), endocrine-disrupting compounds (Mailler et al., 2014) and recently-observed nanoparticles (Joško and Oleszczuk, 2013). Two of the most toxic groups of compounds frequently observed in sewage sludge are polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), which have mutagenic, carcinogenic, and immunotoxic effects, as well as developmental and reproductive effects on living organisms (Gworek et al., 2013; Jackson and Eduljee, 1994; McLachlan et al., 1996; Molina et al., 2000).

The presence of such a wide range of toxic substances in sewage sludge limits its utilization. Although the best use for this waste is its disposal via agricultural use, as in the case of raw sludge, or other composting practices, a significant amount of sewage sludge, typically that from the larger cities, cannot be used as fertilizer due to the excessively high content of heavy metals (Sewage Sludge Directive 86/278/EEC).

An alternative use is by exploitation as a fertilizer for energy plants. This approach not only serves as an effective method of sewage sludge management, but also allows the implementation of the Renewable Energy Sources Directive 2009/28/EC, which requires 15% of total energy to be obtained from renewable sources in Poland, and 20% in the EU; it also allows the Kyoto Protocol to be achieved. In addition, this method would reduce the amount of pollutants in soil, and enable the recultivation of poor quality soil currently left fallow, and which covers 32.3% of land in Poland. The applications of sewage sludge on this kind of soil would restore the circulation of nutrients and improve soil structure and quality.

Among the different crops proposed for energy production and remediation processes, willow (*Salix* sp.) is one of the few that has been planted commercially to a significant extent in the EU (Bernedes et al., 2004; Börjesson, 1999; Elowson, 1999; Ericsson et al., 2006; Labrecque and Teodorescu, 2003; Meers et al., 2007; Vervaeke et al., 2003). Willow plantations provide ecological and renewable raw material for thermal energy. In fact, they absorb carbon dioxide from the atmosphere during vegetative period and their wood emits almost no sulfur or nitrogen compounds during burning. Therefore, unlike the burning of conventional fuels, willow biomass does not contribute to the greenhouse effect or acid rain formation. Moreover, biomass production of willow on poor quality agricultural land can utilize land unsuitable from the production of food, while the phytoremediation properties of willow can be employed in the removal of heavy metals and other toxic

compounds (de Cárcer et al., 2007; Iori et al., 2013; Mleczek et al., 2009; Urbaniak et al., 2013b).

The influence of sewage sludge on soil-plant environment may therefore be both positive, thanks to the nutrient and organic carbon content, and negative, due to the presence of toxic compounds. With this in mind, the aims of the present study were threefold: 1) to recognize the impact that sewage sludge from different size WTPs (small, medium and large) may exert on the properties of soil, with particular regard to the content of organic carbon and humus fractions, bacterial abundance, phytotoxicity measured using three test species (*Sinapis alba* L., *Lepidium sativum* L. and *Sorghum saccharatum* L.), and PCDD/PCDF TEQ concentrations; 2) to determine the impact on these soil properties of using combination of both sewage sludge and willow; 3) evaluate the impact of this sewage sludge on the biometric (biomass, leaf length and leaf surface area) and physiological parameters (chlorophyll content) as well as on the detoxification capability (GST activity) of the willow (*Salix viminalis*), a typical crop used in Poland for energy production and remediation of soil following sludge application.

2. Materials and methods

2.1. Experimental design and sample collection

The soil was obtained from the area of mixed land use type: forest, agricultural and wasteland, located within the Protected Zone of a Lodz Wastewater Treatment Plant (WTP). The soil was of poor quality (Class VI) and mainly composed of loose sands. Before use, soil was analysed for the concentration of heavy metals. All the analysed compounds were between five up to 120-fold lower than the allowable limits for the poor quality soil established by the Regulation of the Polish Minister of Environment (Journal of Laws of 2015, item 257).

The sewage sludge was obtained from three WTPs located in Central Poland, selected according to the following size criterion: small (Class I), medium (Class II), large (Class IV) (Table 1). The WTP size categories are based on Polish regulations (Journal of Laws 2006 no. 137, item 984), wherein the population equivalent (p.e.) and wastewater outflow are the primary factors determining their category: Class I (p.e.: 0–1999; wastewater outflow: 100–300 m³/day); Class II (p.e.: 2000–9999; wastewater outflow: 300–1000 m³/day), and Class IV (p.e.: 15,000–99,999; wastewater outflow: 1500–15,000 m³/day) (Table 1). The obtained sewage sludge was used as a fertilizer in quantities of three and nine tons per hectare (t/ha) reflecting the maximum dose of sewage sludge permitted by the Regulation of the Polish Minister of Environment (Journal of Laws of 2015, item 257). No additional amendment was used.

The experiment was conducted for 20 weeks under field conditions within the Protected Zone of a Lodz WTP. The location of the experiment was selected to replicate the conditions found in the surrounding willow plantation. The meteorological conditions (temperature, rainfall, air humidity and wind speed) over the experiment period are depicted in Fig. 1. The average daily temperature ranged from 15.4 °C at the beginning to 22.1 °C in the mid of experiment and 12.9 °C after 20 weeks. The rainfall over the experiment occurred only on September and October with the highest value on 23rd September. The air humidity varied from 63% at the beginning to 59% after 10 weeks of experiment with the highest value of 84% noted after 20 weeks. The wind speed, in turn, ranged from the highest value of 15 km/h at the beginning of the experiment, through 6 and 7 km/h after 10 and 20 weeks, respectively.

Typical planting procedures for energy plantations were applied: the distances between rows were 1.25 m and between plants 0.5 m. Wells were dug on the plot and filled with previously prepared soil (controls) and mixture of soil and sewage sludge. The control soil as well as mixture of soil and sewage sludge was separated from the surrounding soil by a layer of Teflon foil in order to maintain controlled conditions

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