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Use of sewage sludge in bioenergy production—A case study on the effects on sorghum biomass production

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ABSTRACT

The aim of the study was to determine the effect of different doses of municipal sewage sludge (0, 10, 20, 40, 60 Mg DM ha^{-1}) on sweet sorghum yields and quality as well as changes in physico-chemical and biological properties of the soil. In a three-year field experiment located on loamy clay on an area designated for a landfill site, three sorghum varieties (GK Csaba, Róna 1, Sucrosorgo 506) were tested in order to determine which one exploited the yielding potential of sewage sludge.

It was found out that application of the highest doses of sewage sludge resulted in the highest yield of plants biomass. Among the tested cultivars of sorghum the most productive was Sucrosorgo 506, while the GK Csaba was characterized by the lowest productivity. What is more, the differences in yields of individual varieties were correlated with the level of sewage sludge fertilization. Sucrosorgo 506 generated the highest yields of biomass after the highest doses of sludge application, the best results for the GK Csaba variety were obtained after the application of 40 Mg DM sewage sludge per hectare, while Róna 1 gave the highest yields after applying the smallest doses of sludge. It was also observed that the content, uptake and index of bioaccumulation of macronutrients and heavy metals contained in the sludge increased along with the increasing dose of the applied biosolids, reaching the maximum at 60 Mg DM ha^{-1}. *Sorghum* biomass was characterized by favourable net and gross calorific values, which were the highest in objects with the lowest doses of sewage sludge. The highest energy value of biomass yield was obtained in the case of the Sucrosorgo 506 variety (on average 144 GJ Mg^{-1} ha^{-1}), about 32% lower energy value was found in Róna 1, while the energy value of GK Csaba biomass was by half lower in comparison to Sucrosorgo 506. *Sorghum* tissues bioaccumulated nitrogen and cadmium intensively, zinc, copper, and nickel—at a medium level, and potassium, phosphorous, magnesium, chromium and lead were slightly accumulated. Introduction of the higher doses of municipal sewage sludge significantly affected the physico-chemical properties and enzymatic activity of soil, decreasing its pH but increasing hydrolytic acidity, total nitrogen as well as the concentration of available macronutrients but at the same time the heavy metals content. Municipal sewage sludge contributed to an increase in the organic carbon concentration, which varied primarily due to the different doses of sewage sludge. Sewage sludge introduction also resulted in a marked increase in enzymatic activity compared to the control objects, wherein the activity of dehydrogenases, acid and alkaline phosphatase, protease as well as urease increased progressively with increasing doses of sludge.

1. Introduction

Energy Policy of Poland (2009) and Council Directive (2009) on the promotion and use of energy from renewable sources report that the overall share of energy from renewable sources should be 15% in 2020 and 20% in 2030. In addition, these documents contain provisions for conservation of forest resources and the promotion of energy crops, biomass of which may be used for direct combustion or biofuel production. The latter provision requires the destination for the purpose of energy crops 10% of the Polish national acreage of arable land (i.e., about 1.7 million ha).

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Sweet sorghum (*Sorghum bicolor* (L.) Moench ssp. *bicolor*) from the Poaceae family is one of the promising bioenergy plant, having relatively low input requirements, drought tolerance and ability to maintain high yields under a wide range of environmental conditions (Wight et al., 2012; Ceotto et al., 2014). What is more, this crop contains a significant quantity of fermentable carbohydrates and does not directly compete with food crops (Han et al., 2011). Sweet sorghum is an annual C_4 crop with tall stalks that that can be utilized for forage, silage (Ceotto et al., 2014; Kozłowski et al., 2006; O'Hara et al., 2013) or can be subjected to direct combustion, conversion to bioethanol or as a substrate for biogas production (Monteiro et al., 2012). Its biomass after juice extraction can be burnt in boilers to generate heat and steam for the operation of processing equipment and to generate electricity for both the process and export to the electricity network or may be converted into lignocellulosic ethanol (Rennie and Tubeileh, 2011; Zhao et al., 2012; Gill et al., 2014). It has been reported to have sulphur and ash contents that are 50 and 8 times lower, respectively, than that of lignite and its higher heating value has been measured to be 16.8 MJ kg^{-1} (Rennie and Tubeileh, 2011). *Sorghum* is widely distributed across Africa, Asia and North America and plays an important role among cereal crops, taking the 5th place in terms of acreage (after wheat, rice, maize and barley). Its total global area is above 38 million hectares, while the size of its production is estimated at 57 million metric tons per year (Dweikat, 2012; O'Hara et al., 2013; Gill et al., 2014). In the temperate climate of central Europe sweet sorghum is cultivated mainly as a forage or bioenergy crop, often competitive with maize.

Although sorghum has many traits that make it ideal for biofuel production, environmental and management conditions can affect its productivity (Wight et al., 2012). As shown by many authors (Al-Jaloud, 1999; Akdeniz et al., 2006; Keskin et al., 2009) the species can produce much higher biomass yield after applying a fertilizer, e.g., municipal sewage sludge, which is a source of many valuable nutrients and has a value close to manure, but contains a number of potentially harmful constituents such as heavy metals (Keskin et al., 2009). In addition, the agricultural use of biosolids has been found safe and effective, especially when the total amount of sewage sludge production in Poland is estimated to reach 706.7 thousand tons in 2018 (Werle and Wilk, 2010). The use of sewage sludge could not only increase yields but also positively affects biological and physico-chemical properties of the soil profile (Akdeniz et al., 2006; Singh and Agrawal, 2008; Bielińska et al., 2009; Epelde et al., 2009; Usman et al., 2012). Hence the interest in the use of biosolids in the cultivation of energy crops such as sweet sorghum has been studied by many authors (Al-Jaloud, 1999; Akdeniz et al., 2006; Keskin et al., 2009; Usman et al., 2012).

The primary focus of this study was to determine the impact of different municipal sewage sludge doses on biomass yields and structure. The research hypothesis assumes that municipal sewage sludge used for sorghum fertilization can be a valuable source of minerals for plants not intended for consumption, preferably promoting their growth and development. In addition, the possibility of applying sewage sludge in growing crops for energy purposes could become an alternative to the use of conventional fertilizers and contribute to redevelopment of the main current management method, i.e., storage, which poses a threat to the environment. For this purpose, a field experiment with four levels of municipal sewage sludge doses (10, 20, 40 and 60 Mg DM ha^{-1}), and an untreated control object was established. Efforts were made to assess the impact of sewage sludge on the chemical composition and structure of the experimental plant yield and selected physico-chemical properties as well as enzymatic activity of the soil. The study also attempted to determine the most productive variety of sorghum in the conditions of south-eastern Poland.

2. Materials and methods

2.1. Site description

Three-year (2008–2011) field experiments were established in a landfill belonging to the Janów Lubelski Department of Public Utilities in south-eastern Poland (50°43′17.7″N 22°22′08.0″E). The soil was a clay loam, characterized by slightly acidic pH, average humus content, low phosphorus, potassium and magnesium content, and heavy metal content remaining at the natural level (Kabata-Pendias, 2011) (Table 1). The WRB (2007) classification of the soil is Cambisols.

2.2. Experiment design and sample preparation

The experiment was established as a randomized complete block design with two treatment factors: sewage sludge application and variety on plots with an area of 14.4 m^2 (3 × 4.8 m) with three replicates. Prior to the study the field was fallow, without conventional disk tillage. In September 2007 municipal sewage sludge was applied in doses according to the experiment design and mixed with topsoil. In the spring 2008, several weeks before sorghum planting, the seedbed was prepared by tilling with a mouldboard plough and disk harrow. Seeds of three sorghum varieties were sown in mid-May using a precision sowing machine, at the distance of 0.75 m between rows and 0.07 m within rows. The density of 18 seeds m^{-2} was adopted with the purpose of obtaining a density of 8–10 plants m^{-2}. Under our open field conditions the rate of emergence for sorghum seeds is about 50%.

The experiment comprised five levels of municipal sewage sludge and three sweet sorgum varieties (a tetraploid hybrid variety Róna 1 and Sucrosorgo 506 as well as a hybrid from a cross between *S. bicolor* × *S. sudanense* – GK Csaba). Sewage biosolids were applied only once, before establishment of the experiment, at four rates: I-60 Mg DM ha^{-1}; II-40 Mg DM ha^{-1}; III-20 Mg DM ha^{-1}; IV-10 Mg DM ha^{-1}; the control objects were not fertilized with sewage sludge: V-0 Mg DM ha^{-1}. In the experiment, municipal sewage sludge was used, which contained 13.3% of dry matter, 7.45% of N total and 2.35% of N ammonium (Table 1). The sewage sludge was characterized by relatively low content of heavy metals compared to that found in the literature (Singh and Agrawal, 2008; Werle and Wilk, 2010; Usman et al., 2012). Due to the high water content, it has been mixed with topsoil in autumn of 2007. No irrigation was supplied, and mechanical weeding was applied twice during the growing season.

At the end of September sorghum was harvested in the milk stage of kernel after about 160 days (in 2008–133 days) of vegetation (BBCH 73–77) (Vanderlip, 1993), using hand implements at a stubble height of ca. 10 cm. During biomass harvesting, biometric measurements were performed (number of leaves, plant height and stem diameter at the base of 10 randomly selected plants in each plot). Additionally, ten randomly selected plants from each plot were taken and divided into stem, leaves and a panicle for biomass estimation. Afterwards, all aerial biomass from the plot was chopped in a commercial chipper shredder Bear Cat 70080 s-8HP (Colorado, USA) and three subsamples (600 g, 1000 g and 2000 g) were taken. 600 g subsamples were dried in an air force oven at 70 °C for 48 h in order to adjust fresh mass to a dry matter basis, 2000 g subsamples of Sucrosorgo 506 feedstock were used for its bioenergy characteristics, and three 1000 g subsamples of leaves, stems and panicles from each plot were taken for chemical analysis and dried at 70 °C for 48 h. These subsamples were ground and analyzed for macronutrients and heavy metals by ICP-AES and total nitrogen content by the Kjeldahl method and phosphorus by a spectrophotometer (Ostrowska et al., 1991; Nelson and Sommers, 1975). In order to assess the suitability of the test plants for disposal