Ecotoxicology and Environmental Safety 147 (2018) 86–92

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Long term growth of crop plants on experimental plots created among slag heaps

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ARTICLE INFO

Keywords:
Biosolids
Post-mining area
Reclaimed land
Reuse of material
Phytoremediation
Trace elements

ABSTRACT

Suppression of plant growth is a common problem in post-mining reclaimed areas, as coarse texture of soils may increase nitrate leaching. Assessing feasibility of using solid waste (precipitated solid matter) produced by water and sewage treatment processes in field conditions is very important in mine soil reclamation. Our work investigated the possibility of plant growth in a degraded site covered with sewage-derived sludge material. A test area (21 m × 18 m) was established on a mine soil heap. Experimental plant species included *Camelina sativa, Helianthus annuus, Festuca rubra*, *Miscanthus giganteus, Amaranthus cruentus, Brassica napus, Melilotus albus*, *Beta vulgaris,* and *Zea mays.* ANOVA showed sufficient water content and acceptable physical properties of the soil in each year and layer in a multi-year period, indicating that these species were suitable for phytoremediation purposes. Results of trace elements assays indicated low degree of contamination caused by Carbocrash waste material and low potential ecological risk for all plant species. Detrended correspondence analysis revealed that total porosity and capillary porosity were the most important variables for the biosolids among all water content related properties. Overall, crop plants were found useful on heavily degraded land and the soil benefited from their presence. An addition of Carbocrash substrate to mine soil improved the initial stage of soil reclamation and accelerated plant growth. The use of this substrate in phytoremediation helped to balance the content of nutrients, promoted plant growth, and increased plant tolerance to salinity. Sewage sludge-amended biosolids may be applied directly to agricultural soil, not only in experimental conditions.

1. Introduction

Technological processes coal and metal mining industry contribute to soil degradation (Klatka et al., 2014). There is currently an increasing need to investigate heavy metal contamination (Wang et al., 2007). Studies have been focused on the assessment of heavy metal accumulation in plants, particularly on lands undergoing reclamation (Pietrzykowski et al., 2014; Pająk et al., 2017). Authors have undertaken comparative studies to examine vegetation communities in terms of reclamation of contaminated areas (Latare et al., 2014; Kurowski et al., 2015). Intensive development of soil-forming processes is important in degraded areas. Recently, much attention has been paid to the role of seedlings in the reclamation of mining areas (Kuznetsova et al., 2010). There is currently a tendency to apply amendment mixtures as soil stabilizers or conditioners in the reclamation of mine or agriculture soils. Sewage sludge containing low levels of heavy metals is considered an inexpensive fertilizer in agriculture and land reclamation (Halecki et al., 2016). The use of biosolid amendments in phytoremediation was reported in numerous papers (Obbard, 2001; Vaitkutė et al., 2010; Halecki and Klatka, 2017; Lukić et al., 2017). For example, application of sewage sludge was essential in the cultivation of radish (*Raphanus sativus*), as it improved soil properties, especially its physical and chemical characteristics, and facilitated sustainable agriculture (Lima et al., 2016). However, Kinney et al. (2006) indicated that municipal wastewater treatment plants were a source of organic wastewater contaminants (OWCs), such as hazardous pharmaceuticals, hormones, detergent metabolites, fragrances, plasticizers and pesticides.

The problem is to select an appropriate material for land reclamation. Mining areas may be rehabilitated using cost-effective waste materials such as municipal sewage sludge (Forsberg and Ledin, 2006) or fly ash (Zhang et al., 2008). Hence, the aim of the study was to examine the feasibility of using sewage sludge amendments when post-flotation coal waste, crushed stones and fly ash are used during the remediation process. Reclamation of post-mining areas is problematic due to their poor physical and chemical properties. Another difficulty is a proper choice of the reclamation direction. Degraded soils subjected to remediation are generally characterized by poor vegetation. Our study indicated that phytoremediation was suitable for the management of

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http://dx.doi.org/10.1016/j.ecoenv.2017.08.025
Received 2 January 2017; Received in revised form 9 August 2017; Accepted 11 August 2017
0147-6513/

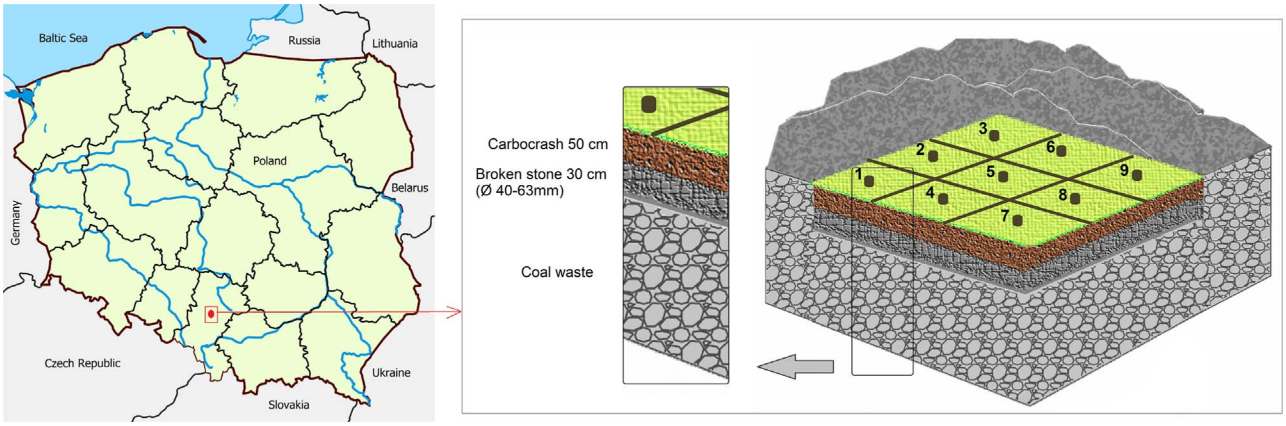

Fig. 1. Location of study area and scheme presenting detailed design of the phytoremediation experiment before plant sowing.

degraded lands. The study has the following objectives: i) to create a new mixture composition containing dewatered sewage sludge and to test the properties of this material (soil conditioner) in soil restoration; ii) to determine the potential of using dewatered sewage sludge with suitable amendments in the reclaimed area; iii) to improve physical and chemical properties of soils during the land reclamation process; and iv) to assess phytoremediation capability of plants. We hypothesized that water content related properties of degraded post-mining soils would be improved by the application of biosolids (disinfected nutrient-rich organic byproduct of wastewater treatment process) that would facilitate crop growth on the forming initial soil.

2. Materials and methods

2.1. Study area

A field experiment was conducted in an industrial area located in a coal and metal mining industry in Zabrze (Poland) – a site heavily contaminated by trace elements (Fig. 1). Wide variety of waste material amendments were tested to obtain a new composite material. We introduced a sewage sludge-amended biosolid called Carbocrash (35% municipal organic sewage sludge, 30% post-flotation coal waste, 20% crushed stone (angular sandstone) and 15% fly ash) to improve the optimal composition for soil restoration. Mine soil remediation was initiated on material with a thin (50 cm) soil surface layer for plant root establishment. Drainage layer of the plot was a rock substrate with fraction diameter of 40–63 mm and 30 cm thickness. Sewage sludge-amended biosolids in the amount of 300 t were added in all experimental treatments.

Sowing period was initiated in 2010. Trees and shrubs most commonly used for phytoremediation purposes were planted on the plots 1–6. However, analysis of development of these plants was not the aim of this study, and was therefore omitted. Contrary to that, vegetation on plots 7–9 as crop rotation in the years 2010–2015 was discussed in details. Before sowing, the plots were covered with fertile mineral soil enriched with organic substances in the form of garden soil. Dimensions of the entire fenced-in study area were 21 × 18 m, and individual plot size was 7 × 6 m (Fig. 2).

Camelina (*Camelina sativa*, Brassicaceae), with a seeding rate of 5 kg/ha, and common sunflower (*Helianthus annuus* L., Asteraceae), with a seeding rate of 14 kg/ha, were selected for the experiment. Additionally, a mixture of early stages of grass seeds (Poaceae) was sown at a rate of 50 kg/ha. The grasses were treated with fungicides and included the following species: Red fescue var. Areta (*Festuca rubra*; 40% of plant cover per plot), Perennial ryegrass var. Envy (*Lolium perenne*; 20%), Tall fescue var. Kilimayaro (*Festuca arundinacea*, syn. *Schedonorus arundinaceus* and *Lolium arundinaceum*; 5%), Perennial ryegrass var. Libronco (*Lolium perenne*; 25%), Sheep fescue var. Noni (*Festuca ovina*; 5%), and Smooth-stalked meadow var. Bila (*Poa pratensis*; 5%). Grass from the first harvest was oven-dried at 85 °C for 18 h and weighed to determine dry matter yield. In 2011, Giant miscanthus (*Miscanthus × giganteus*) was added and amaranth (*Amaranthus cruentus*) replaced *Camelina sativa* in the crop rotation with a seeding rate of 1.0 kg/ha and 30 cm row spacing for both species. In 2012, amaranth replaced common sunflower. In 2013, rapeseed (*Brassica napus*) was sown to improve the quality of the biosolids. In 2014, white sweet clover (*Melilotus albus*) and sugar beet (*Beta vulgaris*) were sown at a seeding rate of 20 kg/ha, at row spacing of 25 cm and 45 × 18 cm, respectively. To improve land reclamation quality, European yellow lupine (*Lupinus luteus*) was introduced into the study area. In 2015, maize (*Zea mays* L.) at 60 × 13 cm row spacing was added to the experimental design. The spacing could be adjusted depending on the target plant populations. The experimental design is presented in Fig. 2. Plant growth is closely related to weather condition, therefore, we provided meteorological data. Mean meteorological data for the years 2010–2015 were derived from the Institute of Meteorology and Water Management - National Research Institute for the station Katowice (Poland). Average annual temperature was 8.9 °C, with annual average maximum of 13.9 °C, and annual average minimum of 3.5 °C. Total annual precipitation was 671.7 mm, and annual average wind speed was 11.6 m/s. Number of days with rain, snow, and storm was 191.5, 60.2, and 35.5, respectively.

2.2. Properties of dewatered sewage sludge amendments

Samples (N = 335) were randomly taken from the vegetation plots. Soil (biosolids) texture was determined by Bouyoucos technique in Casagrande and Prószyński modification (PN-R-04033). Soil studies included samples taken in repetitions from each layer for each parameter, which yielded 67 results per plot. Samples were collected for each of four layers from 0 to 50 cm. Electrical conductivity was determined with a CC 102/1 OK-318 conductivity meter. pH was determined by potentiometry using a C-315 m electronic pH meter. The ratio for the solutions for both parameters, prepared using distilled water, was 1:2.5 (w/v). Biosolid samples (N = 67) taken with 100 cm^3 Kopecky cylinders (rings) were used to calculate the following physical properties (Mocek et al., 1997): mass water content (MWC), volumetric water content (VWC), bulk density (BD), actual bulk density (ABD), specific gravity (SG), total porosity (TP) and capillary porosity (CP). Specific gravity (density of the solid phase) was tested using a pycnometer method in distilled water.

Hydrolytic acidity and cation exchange capacity (CEC) were determined by Kappen's method (Lityński et al., 1976). Exchangeable cations Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the plots were extracted using CH_3COONH_4 at a concentration of 1 mol/L and pH = 7.0. Capacity of the adsorption complex was calculated as a sum of exchangeable basic