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Research article

Phytostabilization of Zn-Pb ore flotation tailings with *Dianthus carthusianorum* and *Biscutella laevigata* after amending with mineral fertilizers or sewage sludge

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A B S T R A C T

Zinc-lead mining wastes remain largely unvegetated and prone to erosion for many years because of phytotoxic levels of residual heavy metals, low nutrient status and poor physical structure. The optimal solution for these areas is to restore plant cover using species which spontaneously appear on the spoils. These species are adapted to the conditions of tailings, and their establishment will promote further vegetation by increasing soil organic matter and development of a soil system capable of supporting the nutrient and water requirements of plants and microorganisms. The potential of *Dianthus carthusianorum* and *Biscutella laevigata* to stabilize mine spoils was analysed in a three-year pot experiment. Post-flotation wastes accumulated after Zn and Pb recovery from ores, were collected from tailings and used as a substrate for plant growth. Seeds for seedling production were collected from plants growing spontaneously on mine tailings. Prior to the establishment of the three-year pot experiment, the substrate was amended with fertilizer NPK or municipal sewage sludge, supplemented with K_2O (SS). Substrate samples were collected for chemical analyses, dehydrogenase and urease activities measurements each year at the end of the growing season. The plants were harvested three years after the amendments. Both tested plant species were equally suitable for revegetation of the tailings. The amendment including both SS and NPK resulted in an increase of C_{org}, N_t, available P, K, Mg contents, an increase of dehydrogenase (DHA) and urease activities and a decrease in the concentrations of the soluble forms of Zn, Pb and Cd. However, nutrient content, DHA activity and plant biomass were higher with SS than NPK addition. NPK application enhanced the substrate properties after the first growing season, while positive effects of SS use were still observed after three years. A longer-lasting positive effect of SS than NPK application was probably due to the high organic matter content in SS, which was gradually decomposing and releasing nutrients.

1. Introduction

Zn and Pb ore deposits have been exploited for centuries in the Olkusz, in SE region of Poland. A mining and metallurgy plant in this region uses a flotation process for ore enrichment. Zn-Pb ores, occurring in dolomites, contain approximately 5% of metals. Each year 3 million tonnes of ores are processed, leaving circa 1.5 million tonnes of flotation wastes stored in sedimentation ponds as fine-grained drift, which contains more than 3% Zn, 1% Pb and 0.01% Cd by weight. The relatively high amounts of Zn and Pb in tailing dumps make them useful for recovery of metals (Grobelak and Napora, 2015; Krzaklewski et al., 2004; Theodoratos et al., 2000; Tordoff et al., 2000). Tailings have been stored for more than 50 years, and currently over 50 million tonnes of wastes have accumulated in 50–60 m high piles over a 110 ha area. This results in areas devoid of vegetation for many years. Without a protective

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plant cover, the surface of a waste settler poses serious risks to the environment and human health due to its high wind and water erosion susceptibility, which facilitates air dispersal of the contaminants (Ciarkowska et al., 2016; Pająk et al., 2015; Zhang et al., 2012). Stabilization is required.

A method to diminish the negative impacts of tailings on the surrounding landscape is to cover them with vegetation. The presence of plants decreases wind erosion by reducingwind speed just above the surface. Water erosion and a risk of groundwater pollution by water flowing through the waste is also reduced as plants capture significant amounts of precipitation. Tailings are a very unfavourable environment for plants due to the high levels of heavy metals in combination with low amounts of macronutrients and organic matter. Another plant growth limiting factor is a low water-holding capacity of flotation wastes that makes them a very dry habitat.

In areas devastated by mining and metallurgical plants, vegetative cover is usually created by sowing grass mixtures or planting different species of trees and shrubs. These species were often of foreign origin and presented a potential threat to indigenous species occurring in the adjacent areas (Hao et al., 2004; Parraga-Aguado et al., 2014). Currently, many research studies reveal that restoration of vegetation in areas polluted with heavy metals, including tailing ponds could be performed by native tolerant plant species. These plants are capable of growth and reproduction under the severe local ecological conditions better than introduced plants originating from other environments (Berti and Cunningham, 2000; Blidar et al., 2009; Muszyńska et al., 2013). Such a plant-based remediation technique is known as phytostabilization. The aim of phytostabilization is not to remove metal contaminants from a site, but to stabilize it and reduce the risk to human health and the environment. Considering the many advantages of phytostabilization such as, low-costs, environmental sustainability, easy implementation, and aesthetic value, this technique has recently attracted wide public attention, especially as an efficient technology for the remediation of mine tailings (Escarré et al., 2011; Meeinkuirt et al., 2013; Wong, 2003).

Biscutella laevigata L. (Brassicaceae) and *Dianthus carthusianorum* L. (Caryophyllaceae) grow naturally on lead-zinc (calamine) waste heaps near Olkusz and exhibit a high tolerance not only to elevated levels of heavy metals but also to a water and nutrient deficit (Baranowska-Morek and Wierzbicka, 2004; China et al., 2014). These features make of them potential candidates for the stabilization of neighbouring mine tailings. Moreover, it could be expected that the pioneer vegetation will improve the physical, chemical and biological properties of the tailings facilitating colonization by plants that do not have such adaptations (Lu et al., 2014).

The addition of nutrients is important to facilitate the establishment and colonization by the pioneer plants (Wong, 2003). There is considerable recent research on the potential of sewage sludge (SS) to stimulate the plant growth on mine land by improving its physical and chemical properties. SS presents a disposal problem and application of SS to soil-free mine ground increases organic matter and plant nutrients (especially N and P) similar to natural organic fertilizers (Jezierska-Tys and Frąc, 2005; Singh and Agrawal, 2007; Sobik-Szołtysek and Jabłońska, 2010; Theodoratos et al., 2000).

In the present study, biological stabilization of Zn and Pb flotation wastes was evaluated through the addition of NPK fertilizer or sewage sludge, and cultivation of dianthus *(Dianthus carthusianorum)* and a mustard (*Biscutella laevigata)* in a three-year pot experiment. Improvements in organic matter, nutrient content and enzyme activity were monitored. The purpose of the experiment was to determine which amendments and plant species are more suitable for the revegetation of Pb-Zn mine tailings.

2. Materials and methods

2.1. Sewage sludge properties

Municipal sewage sludge from the Krzeszowice (SE Poland) treatment plant was used. It was characterized by a neutral reaction, high content of fertilizing elements (i.e., organic C, N, P and Mg), as well as relatively low heavy metal content, which makes it suitable for fertilizer. Potassium (K) was the scarcest nutrient (Table 1).

2.2. Pot experiment

The substrate used for growing plants was recently deposited waste material obtained after zinc and lead ore flotation originating from the sedimentation pond of the Mining and Metallurgy plant in Bukowno. The physicochemical properties of the material, which contained 85% 2–0.063 mm particle size, 13% 0.063–0.002 mm particles and 2% particles <0.002 mm are given in Table 1.

The experiment was conducted in a greenhouse at the University of Agriculture in Krakow (with natural light and no heating) from April 2012 to September 2014 using plastic pots (⌀ 22 cm, height 30 cm) with three holes in the bottom. Each pot was placed on a stand to collect leachates which were poured back into the pot. The treatments consisted of 5.5 kg of air dry post-flotation material which was unamended, or mixed with 135 g of dry SS or mineral fertilizer (1.2 g N, 0.4 g P_2O_5 and 1 g K_2O per pot, in forms of NH_4NO_3, KH_2PO_4 and KCl respectively). Due to low K content SS amendments were supplemented with 0.8 g K_2O/pot. Sewage sludge was applied at 135 g d.m./pot, the maximum amount of sewage sludge permitted in reclamation according to Polish Regulation regarding municipal sewage sludge use. Both amendments were applied once at the start of the experiment.

The amounts of NPK fertilizers were calculated so as to introduce the same amounts of N in both NPK and sewage sludge additions. Substrate without additives comprised the control treatment ($n = 9$). There were 27 experimental pots for each plant cultivation totalling 54 pots plus an exclusion area of 48 extra pots surrounding the experimental units to reduce the edge effect. Sewage sludge or NPK fertilizers were mixed with the flotation wastes for each pot separately. The experimental design was a randomized complete block. During the growing periods (mid-April through October) substrate moisture was maintained at 35% of the capillary water capacity, and reduced to 20% during the winter months.

2.3. Tested plants

Dianthus (*Dianthus carthusianorum* L., Carryophyllaceae) and mustard (*Biscutella laevigata* L., Brassicaceae) were selected as potentially suitable species for phytostabilization because they both had spontaneously colonized the flotation waste material. Seeds were obtained from the Olkusz calamine flora population. Plants were grown from the seed, cultivated in greenhouse

Table 1
Characteristics of sewage sludge and substrate (flotation waste).

	pH	C[a]	N	P	K	Mg	Zn	Pb	Cd
Sewage sludge	7.2	354.9	40.7	20 300	2700	6100	1356	77.1	4.32
Substrate	7.4	1.52	0.09	37.5	34.6	64.2	10 690	8058	85.0

[a] C, N, [$g \cdot kg^{-1}$]; P, K, Mg, Zn, Pb, Cd [$mg \cdot kg^{-1}$].