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Relationships between waste physicochemical properties, microbial activity and vegetation at coal ash and sludge disposal sites

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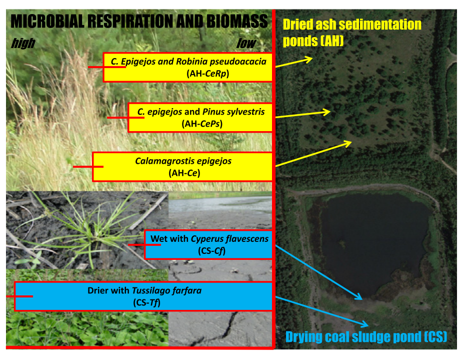
HIGHLIGHTS

- Microbial biomass and activity at coal ash and sludge disposal site were generally low.
- In contrast, plant species richness and cover were relatively high.
- Microbial biomass and activity correlated negatively with C, S, alkali/alkaline earth or heavy metals.
- The admixture of trees to *Calamagrostis epigejos* stands affected few waste parameters.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the study was to assess the relationships between vegetation, physicochemical and microbial properties of substrate at coal ash and sludge disposal sites. The study was performed on 32 plots classified into 7 categories: dried ash sedimentation ponds, dominated by a grass *Calamagrostis epigejos* (AH-*Ce*), with the admixture of *Pinus sylvestris* (AH-*CePs*) or *Robinia pseudoacacia* (AH-*CeRp*), dry ash landfill dominated by *Betula pendula* and *Pinus sylvestris* (AD-*BpPs*) or *Salix viminalis* (AD-*Sv*) and coal sludge pond with drier parts dominated by *Tussilago farfara* (CS-*Tf*) and the wetter ones by *Cyperus flavescens* (CS-*Cf*). Ash sites were covered with soil layer imported as a part of technical reclamation. Ash had relatively high concentrations of some alkali and alkaline earth metals, Mn and pH, while coal sludge had high water and C, S, P and K contents. Concentrations of heavy metals were lower than allowable limits in all substrate types. Microbial biomass and, particularly, enzymatic activity in ash and sludge were generally low. The only exception were CS-*Tf* plots characterized by the highest microbial biomass, presumably due to large deposits of organic matter that became available for aerobic microbial biomass when water level fell. The properties of ash and sludge adversely affected microbial biomass and enzymatic activity as indicated by significant negative correlations between the content of alkali/alkaline earth metals, heavy metals, and macronutrients with enzymatic activity and/or microbial biomass, as well as positive correlations of these parameters with metabolic quotient (qCO_2). Plant species richness and cover were relatively high, which may be partly associated with alleviating influence of soil covering the ash. The effect of the admixture of *R. pseudoacacia* or *P. sylvestris* to stands dominated by *C. epigejos* was smaller than expected. The former species increased N—NH_4, N—NO_3 and arylsulfatase activity, while the latter reduced activity of the enzyme.

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1. Introduction

Mining of bituminous coal and lignite and their combustion for electricity production in thermal power plants generate large amounts of wastes. Coal combustion residues include fly ash (70–75%), bottom ash, slags and flue gas desulfurization materials (Haynes, 2009). Although coal combustion by-products can be used as substitutes for Portland cement in manufacturing of roofing tiles and as structural fills, sheetrock, agricultural fertilizers and soil amendments, large amounts of ash are disposed of by either dry or wet methods in landfills or ponds, which degrades the soil and endangers the environment and human health (Jala and Goyal, 2006; Pandey and Singh, 2010). According to data presented by Pandey and Singh (2010), the largest producers of fly ash, namely India (112 million tons/year), China (100 million tons/year) and USA (75 million tons/year) utilize only from 38% (India) to 65% (USA) of produced fly ash.

Although mineralogical, physical and chemical properties of fly ash and other wastes vary widely, depending on coal type, conditions of combustion, type of emission control devices and handling methods, they are generally considered inhospitable to plants and microorganisms due to their extreme pH, soluble salt concentrations, nutrient deficiency, phytotoxic levels of boron and other elements as well as compaction (Jala and Goyal, 2006; Haynes, 2009; Pandey and Singh, 2010; Adibee et al., 2013; Stefanowicz et al., 2015). Revegetation of waste disposal sites is of primary importance as plant cover stabilizes the ground surface, prevents wind erosion, supplies organic matter, increases nutrient pools, stimulates microbial activity, lowers bulk density, provides shelter for wildlife and enhances aesthetic values of such sites (Haynes, 2009; Arocena et al., 2010; Pandey and Singh, 2012). However, unfavorable physical and chemical conditions of wastes, including fly ash and coal sludge, limit plant growth and slow down the rate of natural plant succession (Roy et al., 2002; Mustafa et al., 2012). Waste disposal sites are usually subjected to technical reclamation, which typically comprises of leveling off the ground, importing topsoil, sowing herbaceous vegetation and planting trees. This approach is considered economically costly and counterproductive for biodiversity, wasting the conservation potential of post-industrial sites, in contrast to spontaneous (or directed) succession (Tropek et al., 2012). It is known, however, that disturbed man-made habitats are often invaded by native or alien expansive plants with low nature conservation potential (Mitrović et al., 2008; Baasch et al., 2012; Stefanowicz et al., 2015). On the other hand, expansive species occurring on waste disposal sites can be considered valuable in terms of effective colonization, phytostabilisation and protection from wind erosion as well the improvement of habitat quality (Mitrović et al., 2008; Stefanowicz et al., 2015).

Calamagrostis epigejos, *Pinus sylvestris* and *Robinia pseudoacacia* are pioneer species that often spontaneously colonize fly ash and other waste deposits and the tree species are planted as a part of technical reclamation (Mitrović et al., 2008; Baasch et al., 2012; Stefanowicz et al., 2010, 2015; Kapusta et al., 2015). They are very tolerant to adverse habitat conditions and able to spread rapidly, presumably due to mycorrhizal associations, specific capabilities such as nitrogen fixation and/or high production of seeds dispersed by wind and long, powerful rhizomes that can spread up to several meters (Rebele and Lehmann, 2001; Mitrović et al., 2008; Colpaert et al., 2011; Vlachodimos et al., 2013; Kapusta et al., 2015; Yang et al., 2015; Józefowska et al., 2017). Being species of contrasting functional traits such as life form, lifespan, growth rate, size, specific leaf area, tissue density, physiology and decomposability of litter produced, *C. epigejos*, *P. sylvestris* and *R. pseudoacacia* are expected to affect differently habitat properties, including physical, chemical and microbial characteristics of soils and wastes (Reich et al., 2005, Orwin et al., 2010, Józefowska et al., 2016).

Calamagrostis epigejos has a negative influence on plant diversity in (semi)natural meadows and grasslands due to high production of aboveground biomass that reduces access to the light. Thick layer of slowly decomposing litter significantly deteriorates the radiation and temperature conditions for the growth of other plant species (Sedláková and Fiala, 2001; Holub et al., 2012). Stefanowicz et al. (2015) showed that *C. epigejos* altered nutrient concentrations and positively affected microbial activity and functional richness of spoil heaps after hard coal mining when compared to bare ground. Leaf litter of a coniferous tree, *P. sylvestris*, is characterized by relatively low Ca and N contents, which has implications for the soil environment (Reich et al., 2005). This species is known to modify nutrient turnover and lower soil pH and Ca concentrations, which can both increase heavy metal mobility in polluted areas and alter ground vegetation (Pallant and Riha, 1990; Augusto et al., 2002, 2004; Reich et al., 2005; Kabata-Pendias, 2011). In contrast, *R. pseudoacacia* is an alien deciduous tree able to fix atmospheric N in symbiosis with *Rhizobium* bacteria. Rice et al. (2004) proved that the invasion of *R. pseudoacacia* into nutrient-poor, pine-oak ecosystems elevated N, P and Ca concentrations, net nitrification and N-mineralization rates in soil, which was associated with high N and low lignin content in its leaf litter. In general, deciduous trees, particularly those that fix atmospheric N, have higher litter quality than coniferous species and more beneficial effects on physicochemical properties and microbial communities in natural soils and post-industrial wastes (Priha et al., 2001; Reich et al., 2005; Šnajdr et al., 2013; Józefowska et al., 2016).

The objectives of the study were to (1) Characterize mining and combustion residues, namely coal ash disposed of by dry and wet methods and coal sludge, as well as soil covering the ash, in terms of moisture, pH, concentrations of macronutrients and heavy metals, microbial activity and biomass, (2) Characterize diversity, cover and composition of vegetation overgrowing the waste disposal site, (3) Assess the relationships between substrate properties, namely moisture, pH, element concentrations, microbial activity and biomass, and plant species composition, (4) Estimate the effects of physicochemical substrate properties on microbial biomass, enzymatic activity, respiration and specific respiration rate (metabolic quotient, qCO_2), (5) Compare the influence of dominant vegetation types, namely *Calamagrostis epigejos*, *C. epigejos* + *Pinus sylvestris* and *C. epigejos* + *R. pseudoacacia*, on physicochemical and microbial properties of the waste disposal site.

2. Materials and methods

2.1. Study area

Disposal site of coal combustion and mining residuals investigated in this study is located in the town of Trzebinia in southern Poland (Fig. 1). The area lies in the transitional climate zone between a temperate oceanic climate in the west and a temperate continental climate in the east. Average annual air temperature fluctuates between 7.1 and 8.1 °C and rainfall between 700 and 873 mm. The growing season spans a period between 205 and 215 days (Lorenc, 2005). The site is located in the excavation after sand exploitation (from 355 to 348 m a.s.l.), covering an area of 41.19 ha. Approximately three quarters of the disposal site is occupied by four dried ash sedimentation ponds and dry ash landfill of the Siersza power plant. The remaining area is occupied by a coal sludge pond of the Siersza hard coal mine. The site is mostly surrounded by planted pine monocultures, impoverished beech forests and extensive sandpit covered with psammophilous grasslands (Woch, 2012; Woch et al., 2017). Other nearby vegetation types include segetal and ruderal communities, meadows, wetlands, and semi-dry calcareous grasslands (Woch, 2005, 2011, 2017; Woch et al., 2013).

2.2. Site types and sampling

Seven categories of study sites were distinguished, depending on both substrate and dominant vegetation types. Three of the seven site categories were located at spatially dominating (19.14 ha) former ash sedimentation ponds (hereafter referred to as AH, ash – hydro sites),