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Stimulation of methane oxidation potential and effects on vegetation growth by bottom ash addition in a landfill final evapotranspiration cover

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ABSTRACT

The landfilling of municipal solid waste is a significant source of atmospheric methane (CH_4), contributing up to 20% of total anthropogenic CH_4 emissions. The evapotranspiration (ET) cover system, an alternative final cover system in waste landfills, has been considered to be a promising way to mitigate CH_4 emissions, as well as to prevent water infiltration using vegetation on landfill cover soils. In our previous studies, bottom ash from coal-fired power plants was selected among several industrial residues (blast furnace slag, bottom ash, construction waste, steel manufacture slag, stone powder sludge, and waste gypsum) as the best additive for ET cover systems, with the highest mechanical performance achieved for a 35% (wt wt^{-1}) bottom ash content in soil. In this study, to evaluate the field applicability of bottom ash mixed soil as ET cover, four sets of lysimeters (height 1.2 m $\times$ width 2 m $\times$ length 6 m) were constructed in 2007, and four different treatments were installed: (i) soil + bottom ash (35% wt wt^{-1}) (SB); (ii) soil + compost (2% wt wt^{-1}, approximately corresponding to 40 Mg ha^{-1} in arable field scale) (SC); (iii) soil + bottom ash + compost (SBC); and (iv) soil only as the control (S). The effects of bottom ash mixing in ET cover soil on CH_4 oxidation potential and vegetation growth were evaluated in a pilot ET cover system in the 5th year after installation by pilot experiments using the treatments. Our results showed that soil properties were significantly improved by bottom ash mixing, resulting in higher plant growth. Bottom ash addition significantly increased the CH_4 oxidation potential of the ET cover soil, mainly due to improved organic matter and available copper concentration, enhancing methanotrophic abundances in soil amended with bottom ash. Conclusively, bottom ash could be a good alternative as a soil additive in the ET cover system to improve vegetation growth and mitigate CH_4 emission impact in the waste landfill system.

1. Introduction

Coal is an important energy resource globally. With the increasing demand for electrical power in the public and private sectors, approximately 8.4 million tons of by-products known as coal combustion byproducts are produced annually in thermal power plants in Korea (Wee, 2013). These include fly ash, bottom ash, boiler slag, and flue gas desulfurization byproducts from advanced clean-coal technology combustors. The fly ash accounts for approximately 80% of the total generated amount of coal ash and is produced in the form of fine powder (1–100 μm diameter). Most of the fly ash from coal combustion is recycled as raw material for cement or cement admixture, while the bottom ash, which accounts for 10–15% of the total amount of coal combustion residues generated in Korea, is less effectively recycled.

Bottom ash is mainly buried or disposed as potential soil waste on-site if there is insufficient disposal storage capacity (Maeng et al., 2014). Coal will continue to be the primary energy source for Korea at least in the near future. Therefore, the disposal of bottom ash is likely to remain a serious environmental issue in terms of waste reclamation, as production is approximately 1.21 million

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tons per year (Maeng et al., 2014). To reduce waste disposal problems, it is necessary to develop technologies for high-volume use of bottom ash. Researchers have long been interested in utilizing waste materials as alternative hydraulic barriers in lining and covering landfills, instead of conventional materials such as clay and other fine soils. This is largely because these earth materials are not always readily available and generally are transported from remote locations, which is costly.

Diverse waste materials have already been used as a substitute for soil-based landfill covers such as fly ash (Mittra et al., 2005), slag from iron and steel-making (Mäkelä et al., 2012), nonferrous slag (Shen and Forssberg, 2003), domestic refuse incinerator ash (Show et al., 2003), overburden materials (Sen and Kumar, 2012), dredged silt (Cesar et al., 2014), construction rubble (Kawano, 1995), wastewater treatment sludge (Aggelides and Londra, 2000), and paper mill sludge (Simpson et al., 1983). Previous studies have reported that bottom ash could be one of the best industrial alternatives among four byproducts (blast furnace and steel refining slags, coal bottom ash, and phosphogypsum) for use in an evapotranspiration (ET) cover system as a landfill final cover system (Kim et al., 2008; Lee et al., 2013; Yun et al., 2010).

The landfilling of municipal solid waste is a significant source of atmospheric CH_4, contributing up to 20% of the total anthropogenic CH_4 emissions (Bogner and Matthews, 2003; Doorn and Barlaz, 1995; Solomon et al., 2007). The IPCC Working Group III assessment report (Börjesson et al., 2007) has listed biocovers/biofilters (i.e., soil covers optimized for the microbial oxidation of CH_4) as key mitigation technologies for landfill greenhouse gas emissions.

Landfill covers or biofilters have been designed to promote optimum growth of methane-oxidizing bacteria (Ganendra et al., 2014, 2015; Yoon et al., 2009). For instance, CH_4 oxidation in the landfill cover layer can potentially remove 0–94% (Börjesson et al., 2001), 95–100% (Huber-Humer, 2004), 21–55% (Barlaz et al., 2004), 4–29% (Laurila et al., 2005), 14–25% (Abichou et al., 2006), 6–38% (Börjesson et al., 2007), and 30–64% (Stern et al., 2007) of the CH_4 generated in the landfill and passing through the top cover. The studies referred to above are from landfill sites with or without gas collection systems, with different cover layer materials and structures, and with potentially different waste composition owing to different waste management strategies.

Typically, ET covers have been considered as final covers that can modulate the percolation of infiltrating rainwater into the waste, balancing the water storage capacity of finer-textured soils with the ability of plants to take up the water stored (Abichou et al., 2015). The ET covers are primarily designed to maintain a higher water storage capacity as well as the ability to efficiently remove stored water by evapotranspiration, preventing water infiltration to the bottom part of the landfill site. As opposed to traditional top cover systems that employ low-permeability barriers, evapotranspiration cover systems may improve conditions for CH_4 oxidation because these may allow water and oxygen to seep in from above as well as allowing the CH_4 generated within the landfill to migrate upwards. The addition of soil amendments such as bottom ash and compost may alter the capacity of landfill cover soils to oxidize CH_4 by influencing both the physical and the chemical characteristics of landfill cover materials such as soil type, moisture content, density and organic and nutrient content, which may influence CH_4 emission by altering the vegetation as well as the physicochemical characteristics in landfill cover soils. The effect of the ET cover on CH_4 oxidation potential has not been explicitly evaluated, in spite of its potential to mitigate CH_4 emissions from landfill cover soils. Here, we study the ET cover system to determine the CH_4 oxidation potential of ET cover soils after the addition of coal bottom ash and compost as potential amendments to stimulate the indigenous methanotrophic community and activity for long-term CH_4 emissions reduction.

2. Materials and methods

2.1. Installation of pilot system

This study was conducted on a pilot scale using the lysimetric methods as previously described by Lee et al. (2013). Four sets of lysimeters were installed on the campus of Gyeongsang National University, Jinju, South Korea, in 2007. Four ET layer compositions, (i) soil + bottom ash (35% wt wt^{-1}) (SB), (ii) soil + compost (2% wt wt^{-1} to promote vegetative growth, roughly corresponding to 40 Mg ha^{-1} at an arable field scale) (SC), (iii) soil + bottom ash + compost (SBC), and (iv) soil only as the control (S), were installed in the experimental lysimeter (height 1.2 m × width 2 m × length 6 m) (Table S1). Before packing, a gravel layer with 10–20-mm grain sizes was introduced for drainage of percolating water. The mixtures were thoroughly homogenized by hand and packed in mid-July 2007.

The soil was collected from an alpine area in Gyeongsang National University campus, Jinju City, South Korea, and air-dried and sieved (<10 mm). It had a pH of 6.1 with low nutrient contents (0.22 dS m^{-1} EC, 14.5 g kg^{-1} organic matter, and 2.7 mg kg^{-1} available P). The selected compost had a pH of 6.8, a total C concentration of 235 g kg^{-1}, a C/N ratio of 24, and 8.3 g kg^{-1} available P. Coal bottom ash was collected from a thermal power plant, the Hadong Power Plant (Kwangyang, South Korea), which was alkaline (pH 9.1) and had higher nutrient concentrations than typical alpine soil: total C content of 41 g kg^{-1}, available P content of 243 mg kg^{-1}, and an EC 3.0 dS m^{-1}. Other coal bottom ashes were collected from other power plants (n = 9) in South Korea for analysis to evaluate variability among the sampling sites as well as to determine whether our findings are applicable to other bottom ash samples (Table S2).

2.2. Evaluation of vegetation growth characteristics

To evaluate the effect of compost and bottom ash as a soil amendment on vegetation in the landfill cover soils, five plant species (*Amorpha fruticosa*, *Artemisia princeps*, *Arundinella hirta*, *Lespedeza cuneata*, and *Lespedeza cyrtobotrya*) were used as cover vegetation; these plants are commonly used in Korean landfill sites (Lee et al., 2013). The plants were manually seeded and covered by a thin layer of soil in mid-July 2007. Thereafter, no chemical fertilizer was added due to maintaining the actual management system in landfill cover soils during 5 years. The above-ground plant biomass was harvested from three 1-m^2 plots from each treatment in late November of the 5th year after the installation to evaluate both grass and shrub biomass growth. The harvested plant material was oven-dried at 65 °C for 72 h and weighed to determine the dry weight.

2.3. Evaluation of methane uptake rate

Bulk soil was obtained from the top of the cover layer (0–15 cm) with three replications from each treatment after plant harvest and sieved (<2 mm). Ten grams of fresh soil (n = 3) was placed into a 120-ml sterile serum bottle and sealed with a silicon rubber stopper. The headspace was flushed with compressed air for 5 min prior to the addition of 0.17 ml of 99.9% CH_4 (Supelco, USA), corresponding to 1500 ppmv in the headspace. Incubation was performed at 30 °C in the dark. The changes in CH_4 concentration in headspace were monitored over 1000 h. Methane concentrations in the headspace were measured by a gas chromatograph (Shimadzu, GC-2010, Japan) packed with a Porapak Q column (Q 80–100 mesh) and equipped with a flame ionization detector (FID). The temperatures of the column, injector and detector were