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Biocomplex textile as an alternative daily cover for the simultaneous mitigation of methane and malodorous compounds

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ABSTRACT

Space-saving biocomplex textiles, which can be used as covers or rolled up as needed, have been demonstrated as alternative daily covers for the simultaneous mitigation of greenhouse gases (GHGs) and odors in landfills. The biocomplex textiles were made by inserting inorganic biocarriers (perlite (P), tobermolite (T) and their mixture (P/T)) between nonwoven fabrics. Methane (CH_4) and dimethyl sulfide (DMS) were used as model compounds for GHGs and odors, and a CH_4 and DMS co-degrading microbial consortium was used as an inoculum source. CH_4 and DMS could be biologically degraded by methanotrophs and sulfur-oxidizing bacteria in the biocomplex textiles. Both biocomplex textiles made with either P or T were able to maintain the removability for CH_4 and DMS after storage for 70 days, although their removal efficiencies for CH_4 and DMS were 70–71% and 62–65% of those before storage, respectively. CH_4 and DMS were simultaneously removed in lab-scale landfill simulation reactors employed with the biocomplex textiles. After 17 days of starvation, only 2–3 days were needed to recover their removability. Among the 3 kinds of biocarriers evaluated, the biocomplex textile generated using the P/T showed the highest removability and was the most stable. The maximum elimination capacities of the biocomplex textile generated with the P/T were 11.5 g-CH_4·m^{-2}-fabric·d^{-1} and 0.5 g-DMS·m^{-2}-fabric·d^{-1}, respectively. These results suggest that the biocomplex textiles are promising alternative daily covers to mitigate the emission of greenhouse gas and odor in operational landfills.

1. Introduction

Landfill gases (LFGs) generated during the anaerobic decomposition process of organic matter consist of 45–60% methane (CH_4), 40–55% carbon dioxide (CO_2), and trace malodorous compounds (USEPA, 2011, 2015). CH_4 is a representative greenhouse gas (GHG) that accelerates climate change because its global warming potential (GWP) is 25 times higher than that of CO_2 over 100 years (IPCC, 2014). Huber-Humer et al. (2008) has reported that a significant amount of CH_4 (35–69 Tg-CH_4 y^{-1}) is released to the atmosphere from operational landfill sites. Since the flammability limit of CH_4 in the air is 5–15%, CH_4 can cause landfill fires (Bagchi and Bhattacharya, 2015). Malodorous compounds (e.g. H_2S, methanethiol (MT), dimethyl sulfide (DMS), dimethyl disulfide) are also released from landfills and can cause not only unpleasantness, but also physical disabilities such as gastroenteric trouble, headache and cardiatic disease (Fang et al., 2012; Shon et al., 2005). CH_4 and non-methane volatile organic compounds among LFGs contribute to the global warming (Collins et al., 2002).

Biological treatment systems for the reduction of LFGs emissions, such as biowashers, biomembranes, biofilters, biowindows, and biocovers, have been studied by many researchers (Abushammala et al., 2014; Huber-Humer et al., 2008; Kim et al., 2013; Lee et al., 2014; Moon et al., 2014). Among these systems, the representative system is a biocover composed of a waste layer, a gas distribution layer, and a microbial layer (Abushammala et al., 2014). Gas distribution layers consisting of core sand or gravel are an essential part of biocovers because they can transmit LFGs from the lower waste layers to the upper microbial layers (Abushammala et al., 2014). Organic matter, such as soil, compost, and sludge, is commonly used as a packing material for microbial layers. These materials have abundant nitrogen (N) and phosphorus (P), which are vital nutrients for microbial growth; hence, microorganisms inhabiting the microbial layers can efficiently degrade LFGs (Ganendra et al., 2015).

However, biocovers cannot installed in operational landfills, and they can be applied only in inactive cells or layers of landfill where landfilling of waste has finished. To eliminate LFGs emitted

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from engaged landfills, the working area is covered with a 15-cm-thick soil layer, which is called the daily cover (DC), in many countries. These days, a variety of alternative daily cover (ADC) materials are used in place of soil: municipal waste compost, composting yard waste, construction & demolition fines, commercial & industrial fines, woodchips, and modified sewage sludge (sludge: lime: cement: silt: tire-derived aggregate = 100:15:5:70:15, w/w) (He et al., 2015; Hurst et al., 2005; Solan et al., 2010; van Haaren et al., 2010). The LFG removal efficiency (RE) of ADCs reaches only 30–40%, and the volume of ADCs required results in a narrow space for waste filling (Huber-Humer et al., 2008). ADCs that have high organic matter content are easily degraded by microorganisms during prolonged use and cause channeling (Nikiema and Heitz, 2010).

To overcome the limitations of conventional ADCs, it is necessary to develop a new ADC that has satisfactory LFGs removability, resistance to biological deterioration, and long-term stable performance. In this study, space-saving biocomplex textiles, which can be used as covers or rolled up as needed, were designed as ADCs. The biocomplex textiles were made by inserting biocarriers between nonwoven fabrics. Perlite, tobermolite, and a mixture of perlite and tobermolite were used as the biocarriers for immobilizing microorganisms. CH_4 and DMS were used as model compounds for GHGs and malodorous compounds emitted from landfills, respectively. The degradation rates and simultaneous removal of CH_4 and DMS by biocomplex textiles in a lab-scale were investigated according to type of biocarrier and storage period. In addition, the effects of starvation on the performance of the reactor were evaluated. Methanotrophic dynamics were quantitatively monitored using a quantitative real-time polymerase chain reaction (qRT-PCR) method to clarify the effect of starvation and operation period on methanotrophic activity.

2. Material and methods

2.1. Cultivation of a CH_4/DMS co-degrading microbial consortium

Earthworm casts obtained from the Nanji water recycling center (Goyang, Kyunggi, South Korea) were used as an inoculation source for the CH_4/DMS co-degrading microbial consortium. Properties of earthworm casts were measured according to the Korean standard methods for soil (2013). Water content, organic matter content, and the pH of earthworm casts were 64.3 ± 0.4%, 71.2 ± 0.1%, and 7.7 ± 0.0, respectively. Earthworm casts were passed through a 2-mm sieve and placed in an air permeable sack kept in the shade at room temperature before being used.

Two g of earthworm casts were added to 600-mL serum bottles containing 18 mL of nitrate mineral salt (NMS) medium, and then the serum bottles were sealed with butyl-rubber stoppers. CH_4 gas from a CH_4 gas cylinder (99%; Seoul Specialty Gases Co., Ltd, Seoul, South Korea) and DMS from a DMS solution (99%; Acros Organics, Geel, Belgium) were injected into the serum bottles to generate final headspace gas concentrations of 50,000 $\mu L \cdot L^{-1}$ and 5000 $\mu L \cdot L^{-1}$, respectively. Incubation was conducted at 30 °C with agitation (150 rpm). The detailed medium composition and enrichment culture condition were as described by Lee et al. (2013). The CH_4/DMS co-degrading microbial consortium cultivation obtained from this procedure was used as the inoculation source for this study.

2.2. Biocarriers and fabric

Perlite (Kyungdong One, Seoul, South Korea) and tobermolite (Jawoo Bio, Daejeon, South Korea) were used as biocarriers for microbial immobilization. Our previous study confirmed that these 2 biocarriers did not adversely affect microbial activity (Jeong et al., 2013). The bulk density, water holding capacity, pH, water content, and organic matter content of perlite were 0.1 ± 0.0 $g \cdot cm^{-3}$, 60.0 ± 7.1% (v/v), 6.7 ± 0.1, 0.1 ± 0.0%, and 0.4 ± 0.0%, respectively. The bulk density, water holding capacity, pH, water content, and organic matter content of tobermolite were 0.6 ± 0.0 $g \cdot cm^{-3}$, 87.5 ± 3.5% (v/v), 7.2 ± 0.0, 2.1 ± 0.0%, and 5.9 ± 0.0%, respectively.

Polypropylene nonwoven fabric (Kyungdong One) with a thickness of 0.3 cm was used as a textile to wrap the biocarriers. The effects of nonwoven fabric on the activity of the CH_4/DMS co-degrading consortium were evaluated as follows: 10 pieces of nonwoven fabric cut into 1 cm × 1 cm pieces were placed in a 120-mL serum bottle, and 2 mL of the CH_4/DMS co-degrading consortium was inoculated onto the nonwoven fabric. After the inoculated nonwoven fabric was dried for 2 days in a fume hood, 2 mL of the NMS medium was added into the serum bottle. The serum bottle was sealed with a butyl-rubber stopper, and CH_4 and DMS were then injected into the serum bottle to generate final headspace gas concentrations of 50,000 $\mu L \cdot L^{-1}$ and 5000 $\mu L \cdot L^{-1}$, respectively. During incubation of the serum bottle at 30 °C with 150-rpm shaking, the headspace gas of the bottle was periodically sampled using a gas-tight syringe to analyze the CH_4 and DMS concentrations. The serum bottle prepared by the same procedure without inoculation of the CH_4/DMS co-degrading consortium was used as a control. All experiments were conducted in triplicate.

2.3. Preparation of the biocomplex textile and evaluation of microbial activity after a storage period

The biocomplex textiles were prepared as shown in Fig. 1. Nonwoven fabric cut into a 12 cm × 22 cm piece and folded in half was sealed along 3 edges using a heat sealer (SK-410; Sambo Tech Co., Ltd, Kimpo, South Korea) to form a pocket. Subsequently, the nonwoven fabric pockets were filled with 100 cm^3 of biocarrier (perlite or tobermolite), inoculated with 40 mL of CH_4/DMS co-degrading microbial consortium and the open unsealed side was heat-sealed to close the pocket. Completed biocomplex textiles wrapped in nonwoven fabric and placed in an air-tight plastic container to prevent dehydration were stored in a shady place at room temperature for 70 days. Subsequently, 40 cm^3 of biocarrier was transferred to a 600-mL serum bottle containing 2 mL of the NMS medium, and CH_4 and DMS were injected into the serum bottle. The serum bottle was incubated at 30 °C with 150-rpm shaking, and the headspace of the bottle was sampled periodically to analyze CH_4 and DMS concentrations. All experiments were conducted in triplicate.

2.4. CH_4 and DMS mitigation in the lab-scale landfill simulation reactor using a biocomplex textile

The lab-scale landfill simulation reactors were prepared to evaluate the applicability of biocomplex textiles for simultaneous mitigation of CH_4 and DMS (Fig. 2). The dimensions of the lower and upper layers of outer reactor were ID 300 mm × H 200 mm and 300 mm × 400 mm, respectively.

Artificial gravel (Hyuga pumice, Japan) and sand were used as filling materials for the inner reactors (ID 200 mm × H 200 mm) in order to have even gas distribution through the cross section of the reactor. Two types of artificial gravel whose diameters were 10–15 mm and 20–30 mm were mixed in a 1:1 (v/v) ratio. Sand sieved using a 2-mm sieve was wetted with tap water to a 20–25% water content. The inner reactor filled with 5000 cm^3 of the artificial gravel and 1000 cm^3 of sand from bottom to top was covered with biocomplex textiles in which the enveloped nonwoven fabric (Φ = 200 mm) was filled with 160 cm^3 of biocarriers inoculated with the CH_4/DMS co-degrading consortium. Three types of

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