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Short Communication

Gradient packing bed bio-filter for landfill methane mitigation

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HIGHLIGHTS

- Vermi-compost (VC) is more suitable for CH_4 mitigation systems than other biogenic materials.
- CH_4 oxidation rates of VC at 25 and 37 °C was similar, thus suitable for tropical settings.
- High-aerophilic and moisture contents affect the CH_4 oxidation capacities of VC.
- Gradient packed bed VC system was found robust than conventional design for CH_4 mitigation.

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ABSTRACT

We assessed the suitability of various biogenic materials for development of a gradient packed bed bio-filter to mitigate the methane (CH_4) emission from landfills. Five different biogenic materials (windrow compost-WC; vermicompost-VC; landfill top cover-LTC; landfill bottom soil-LBS; and river soil sediment-SS) were screened. Among these materials, the VC showed a better CH_4 oxidation potential (MOP) of 12.6 μg CH_4 g_{dw}^{-1} h^{-1}. Subsequently, the VC was used as a packing material along with wood chips in proto-type bio-filters. Wood chips were mixed at 5–15% to form three distinct gradients in a test bio-filter. Under the three different CH_4 loading rates of 33, 44 and 55 gCH_4 m^{-3} h^{-1}, the achieved MOPs were 31, 41, and 47gCH_4 m^{-3} h^{-1}, respectively. The gradient packed bed bio-filter is effective for landfill CH_4 mitigation than the conventional bio-filter as the latter shows gas channeling effects with poor MOPs.

1. Introduction

Landfills are the integral part of municipal solid waste (MSW) management in many countries. Within the landfills, the deposited MSW is decomposed with subsequent emissions of landfill gases (LFGs; Powell et al., 2015). The LFGs include methane (CH_4), carbon-dioxide (CO_2) and traces of hydrogen sulfide, nitrous oxide and other volatile organic components (Nikiema et al., 2007). CH_4 is a potent greenhouse gas (GHG) and their global warming potential is 25 times higher than that of CO_2 (Nikiema et al., 2007). Approximately 88 million tons of CH_4 are reported to be released from landfills, which represent the 3rd largest anthropogenic emission source of CH_4 globally, with agricultural activities and coal mines being the first and second contributors. Thus, the monitoring, control and treatments of LFGs to reduce the CH_4 associated environmental hazards are of global concern and highly significant (Powell et al., 2015). The CH_4 emissions occur continuously that the flow and concentrations vary for many landfills based on their age, waste compositions, operation sequences, local climatic conditions etc., (Powell et al., 2015). Nonetheless, during the active phase of MSW degradation in landfills (i.e., young landfill with 5–30 years age) the LFGs are characterized with a high CH_4 content of ~30–60%. They are collected and treated by thermal routes for energy recovery in larger landfills or wherever it is economically feasible (Powell et al., 2015). The LFG emissions could be fugitive, with the CH_4 concentrations of <20%, were the thermal technologies are less likely to be serviceable (Scheutz et al., 2014; Powell et al., 2015).

Alternatively, biological CH_4 oxidation systems such as bio-filters or bio-windows are effectively tested in few landfills from United States of America, Germany, Denmark, Australia and Canada (Streese and Stegmann, 2005; Nikiema et al., 2007; Huber-Humer et al., 2009; Dever et al., 2011; Scheutz et al., 2011). The operation parameters for such bio-engineered CH_4 mitigation systems are more controllable, reliable, economically

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viable, easy to deploy, more flexible to operate under varying CH_4 concentrations as in landfills. These systems are reported to have a high CH_4 uptake capacity of >100–200 g CH_4 m^{-2} day^{-1} (Nikiema et al., 2007; Scheutz et al., 2011, 2014; Huber-Humer et al., 2009; Dever et al., 2011), since they provide controlled environmental conditions for the methane oxidizing bacterial community (MOB) to proliferate *in-situ* and convert CH_4 into CO_2 (Streese and Stegmann, 2005). These bio-engineered CH_4 mitigation systems either use stabilized solid waste from landfills, compost, dewatered sludge, yard waste or forest/agricultural soils, sediments as packing materials (Huber-Humer et al., 2009; Huang et al., 2011). These biogenic materials (i) naturally harbor a MOB; (ii) are cheap and locally available; (iii) hold essential micro–macro nutrients; and (iv) have high water holding capacities. However, natural bulking properties and channeling/clogging effects of these biogenic materials often lead to poor CH_4 oxidation in bio-engineered settings (Streese and Stegmann, 2005).

The void pore sizes/spaces determine the water and gas distributions, and thus support the rate of gas exchange within the systems and growth of MOB for CH_4 conversion (Streese and Stegmann, 2005; Gebert et al., 2011). Under great bulking or water logged conditions, the CH_4 oxidation rates were expected to be affected due to limited oxygen diffusions (Streese and Stegmann, 2005). In general, 1 mol of CH_4 conversion required 1.5–2 mol of oxygen for efficient CH_4 conversion *in-situ* (Haubrichs and Widmann, 2006). Thus, by improving the bulking properties and selection of appropriate biogenic materials the said effects could be greatly minimized in bio-engineered systems (Streese and Stegmann, 2005). In addition, there are few other challenges that remain in the selection of biogenic materials and designing of bio-engineered systems for real field applications i.e., nutrient depletion and reduced water holding capacities over a time (Dever et al., 2011). Huber-Humer et al. (2009) provided a detailed review and prescribed standards for selection of appropriate biogenic materials for bioengineered systems. However, the appropriate addition of bulking agents and packing designs are still inconclusive to provide better bio-engineered systems for CH_4 mitigations from landfills. The present study proposes a novel design i.e., a gradient packed bed bio-engineered (bio-filter) system, to facilitate better CH_4 oxidation rate for LFG treatment. Five different biogenic packing materials were initially screened for their CH_4 oxidation potential (MOP) under defined test conditions and the most stable/robust substrate was chosen for testing in proto-type bio-filter. The proposed gradient packed system was tested against conventional bio-filter under three different LFG (CH_4) loading rates. The obtained results are compared and discussed.

2. Methods

2.1. Characterization and selection of biogenic packing materials

Five different biogenic materials of ~5 kg were collected from point sources, namely, (i) windrow-compost (WC) – 2 months hold composted horticulture waste and wood chips; (ii) vermi-compost (VC) – 1 month old composted mushroom logs using *Perionyx Excavatus* and *Esienia Foetida*; (iii) river soil sediment (SS) – East coast park river sediment, Singapore; (iv) landfill top (LTC) and (v) bottom soils (LBS) – both were collected from Tampanies landfill, Singapore. All samples were stored at 4 °C and sub-samples were used for physiochemical and biological analysis. The total and volatile solids (TS and VS), the concentrations of ammonium (NH_4^+) and phosphate (PO_4^{3-}) ions were analyzed using standard protocols (APHA, 1998 and Behera, 2006). Elemental analyzer was used for Carbon–Hydrogen–Nitrogen–Sulfur analysis (CHNS; Vario MACRO cube elemental analyzer, Germany). Biogenic samples were acid digested (i.e., aqua regia) for determination of total metal extraction, followed by dilution, for analysis using inductively-coupled plasma-optical emission spectrometer (ICP-OES, Perkin-Elmer, Optima 3000V). Mixed-metal standard solution was obtained Sigma–Aldrich for ICP-OES analysis (TraceCERT®, 33 elements, Sigma–Aldrich, Germany). Cation Exchange Capacity (CEC) was evaluated using $BaCl_2$ compulsive exchange method as detailed elsewhere (Gillman and Sumpter, 1986). Water extracts of biogenic materials were screened for soluble nitrate (NO_3^-), nitrite (NO_2^-) and sulfate (SO_4^{2-}) using ion chromatography.

2.2. Methane oxidation potential (MOP) of biogenic materials

The MOPs of biogenic materials (~10 g) were individually tested using 100 mL serum vials. Simulated LFGs (CH_4 – 60% and CO_2 – 40%; SOXAL Pte., Ltd., Singapore) with oxygen at 1:1 ratio were filled in the head space of serum vials. The head spaces of all vials were vacuumed before purging the LFGs and oxygen mixture. The MOP was measured over a period of 28 days of incubation period and at 37 °C for each sample in triplicate. The gas composition from head spaces was measured for all test vials at different time intervals (day – 1, 3, 5, 15 and 28) by gas chromatography, equipped with thermal conductivity detector (GC-TCD; SHIMADZU GC-17A, Singapore) and the MOP was calculated (Chidamba rampadmavathy et al., 2015). The biogenic material that had shown a high rate of MOP was subsequently subjected to different environmental test conditions in three batches. Batch I was tested at two different temperatures i.e., 25 and 37 °C, which was expected to reveal the robustness of the substrate for field applications and bio-filter design effectiveness (Streese and Stegmann, 2005). Batch II took into consideration the different oxygen to CH_4 mixing conditions and was simulated in headspace i.e., 0:1, 1:1 and 2:1. This was considered mainly to understand the MOPs with and without oxygen under gradient packing system. In gradient packing system, the rate of oxygen diffusion from top to bottom of the bio-filters was expected to be dissimilar (also possible in conventional packing system). In batch III, the saturation effects of moisture were tested at 3 different levels i.e., 1, 3 and 5 mL with 10 g of selected biogenic material in a serum vials. The motivation was to understand the rain water percolation effects on MOPs during bio-filter operation under natural settings. Otherwise, the test conditions maintained were the same as above. The MOPs were calculated and averaged for comparison.

2.3. Design and evaluation of proto-type systems as gradient packing bed bio-filter

Two proto-type bio-filters were fabricated (leak proof acrylic columns) with a total height of 1 m (inner diameter – 0.1 m) and with a packing bed height of 0.8 m (total packing volume – 6.4 L; S1). The test bio-filter was packed with a selected biogenic material (from Section 2.2) and wood chips as a bulking agent. The wood chips of 5–15% were mixed with the selected substrate to create three different bulking gradients and packed in a bottom-up approach to form low to high gradients in a test bio-filter. Another bio-filter used uniform packing i.e., 5% wood chips that was act as a control. Wood chips were found to be the best bulking material (i.e., providing sufficient porosity) to avoid any natural compaction of substrates and channeling of gas/leachate in bio-filters (Streese and Stegmann, 2005). Glass beads of 0.5 cm were used as intermediate diffusion layers to differentiate the gradient packing in the test bio-filter, which could be replaced by gravel layers during field applications or any other supporting materials that can provide better gas diffusions (Streese and Stegmann, 2005). Activated carbon was used in both the bio-filters as final top cover as a CH_4–CO_2 trap, while coconut