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Pilot scale evaluation of a model to distinguish the rates of simultaneous anaerobic digestion, composting and methane oxidation in static waste beds

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ABSTRACT

The aim of this paper was to apply and validate a model for measuring the rate and extent of anaerobic digestion, composting and CH_4 oxidation in laboratory scale beds. Degradation studies were performed in four reactors each packed with shredded unsorted municipal solid waste, with one bed covered with a 100 mm layer of soil. The rates of production of CH_4, CO_2, ^{13}C-CO_2 and the rate of consumption of O_2 were measured and used as inputs to a mass balance expressions for these components to calculate the rates of anaerobic digestion, composting and CH_4 oxidation. The results showed that anaerobic digestion, composting and CH_4 oxidation occurred simultaneously in both the covered and uncovered beds. The analysis showed that 50 ± 4% of the solids (COD basis) in the uncovered beds degraded anaerobically, with the generated CH_4 subsequently oxidized, and that 32 ± 4% of the solids degraded aerobically in the covered bed.

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1. Introduction

The most common destination for municipal solid waste (MSW) worldwide is in static piles, whether this be engineered landfills or open dumps in under developed communties. The extent that waste degrades aerobically or anaerobically affects the methane yield and therefore, the potential amount of methane that could be captured and utilised or emitted from the waste. In terms of regulatory practice, degradation in engineered landfills is assumed to be entirely anaerobic, while 60% and 20% of waste is assumed to degrade aerobically in shallow and in deep unmanaged landfills respectively (IPCC, 2006) However, there is curently no method for validating these estimates from direct measurements of a static waste pile, whether this be landfill, open dump or even a static compost heap.

In terms of evidence of aerobic decomposition in static piles of waste, most research has been performed on landfilled waste with a soil cover. It is well established that gas exchange can occur across a soil cover (Kallel et al., 2006). Measured profiles of O_2 concentrations in landfill have shown O_2 penetrating to 1 m in the waste bed (Kjeld, 2014; Widory et al., 2012).

The presence of aerobic degradation activity as the result of O_2 penetration is well established in studies of soil covers (Abichou et al., 2006b; Christophersen & Kjeldsen, 2000; Gebert et al., 2011), but the extent of aerobic degradation in the underlying waste remains relatively unexplored. Measurements of low fluxes of CH_4 and high fluxes of CO_2 from daily covered surfaces (e.g. Bogner et al., 2011; Abichou et al., 2006a) and uncovered waste surfaces (e.g. Abushammala et al., 2013) have indicated aerobic process in bare or thinly covered waste beds.

Pommier et al. (2008) studied the effect of 15 days of headspace aeration on the degradation of beds of rapidly (e.g. food) and slowly (e.g. paper and cardboard) biodegradable waste and showed that 3–23% of the ultimate BOD of the paper/cardboard fraction was consumed and that about 60% of the BOD of food and yard waste fraction was consumed in that time.

Heat budget studies have further indicated significant aerobic degradation in landfill cells. A dramatic temperature rise within fresh waste covered with a thin layer of soil was reported in numerous studies (Bonany et al., 2013b; Hanson et al., 2013; Lefebvre et al., 2000; Yeşiller et al., 2005). In particular, Lanini et al. (2001) identified aerobic processes as the main source of heat with more than 80% of the consumed O_2 diffused from the

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atmosphere into the waste bed. Further investigation confirmed the same trend in the field (Bonany et al., 2013a).

The aim of this study was to measure trends in CO_2, CH_4 and ^{13}C-CO_2 fluxes and O_2 consumption in packed beds of waste with an aerated headspace and use this data to validate a mass balance model for determining the rate and extent of anaerobic digestion, composting and CH_4 oxidation in the beds. This model is applicable to any static waste pile configuration, whether this be landfill, open dumps or compost piles. The model was validated by (i) comparing predicted rates with the rate of COD consumption in the bed according to the rates of CH_4 production and O_2 consumption; and (ii) by comparing the cumulative COD consumption according to the model with the difference in the COD of the input and residual solids.

2. Materials and methods

2.1. Waste collection and characterisation

400 kg of fresh Municipal Solid Waste (MSW) was randomly collected from the working face of the Swanbank landfill (Ipswich, Queensland). The collected waste was mixed and shredded to less than 10 cm particle size using a tub grinder and stored in air tight drums at −20 °C until the reactors were loaded the day after waste collection. The waste loaded to each reactor was sampled separately by collecting 3–4 kg of random grabs as the reactor was loaded. The sample from each reactor was analysed for TS, VS, COD and biochemical methane potential (BMP). TS and VS were determined using standard method (Method 2540 G, APHA). The BMP assay was performed on three 1 g VS samples of macerated waste (1–5 mm) according to the method described in Lay et al. (1999). The BMP tests were run for 40 days at 37 °C, using mesophilic digested sludge from a local wastewater treatment plant, added at a ratio of 2 parts sludge to 1 part waste on a VS basis. CH_4 and CO_2 were measured using a Perkin–Elmer GC-TCD (AutoSystem GC, Perkin–Elmer, Waltham, MA, USA) as described in Xie et al. (2016). COD was measured using the potassium dichromate/sulphuric acid method with Spectroquant® test kits and Spectophotometer SQ118 (Merck, Germany) based on Standard Method 5229D (APHA, 1998).

The same analyses were performed on the residual waste remaining in the reactors at the end of the experiment. 1 kg samples of residual waste were collected from the top, middle and bottom of each bed at the end of the experiments. A subsample of residual waste from each of these layers was blended to form a composite sample for TS and VS, COD and BMP measurements.

2.2. Set-up and operation of reactors

The reactors were operated as in-vessel static composting units with headspace ventilation to simulate the exposure of fresh landfilled waste to the atmosphere. The reactors were fabricated from stainless steel and consisted of a working volume (cylindrical, ID = 470 mm, Height = 1000 mm) and an underlying conical sump (350 mm deep), with a mesh plate supporting the waste bed above the sump (Chugh, 1996). Leachate was allowed to accumulate in the sump and was recirculated weekly through a distributor on the underside of the reactor lid over the surface of the waste bed. Temperature in the reactors was maintained at 30 °C (the average summer daily maximum temperature in Brisbane) by a 450 W heating tape (Thermal Electric Elements, SS Braided Heat Trace) wrapped around the exterior surface of reactors. The reactor was insulated with 50 mm thick aluminum foil faced glass wool as the outermost layer around the reactor. The reactors were filled with shredded waste to a depth of 850 mm by tamping the waste to eliminate large voids. Despite efforts to shred and homogenise the waste, the amount of waste required to fill each reactor to a depth of 850 mm varied. The densities achieved in the waste beds (Table 1) was significantly less than that in landfills, but was sufficient for anaerobic and aerobic activity to develop in the beds and hence provide data to validate the mass balance model. A 100 mm layer of moistened silty loam, collected from the soil cover inventory at the Swanbank landfill, was added to the surface of one bed (R3). In total, the experiment consisted of 3 replicated uncovered beds (R1, R2 and R4), and 1 soil covered bed (R3), as described in Table 1. The experiments were designed in this manner to explore the reproducibility of degradation behaviour in identically treated beds and to explore the effect of soil coverage on the three biodegradation processes, although this could only be indicative given the higher compaction densities achieved in landfill.

After sealing the reactors, the experiment was initiated by adding approximately 20 L of water to each bed to provide enough leachate to recirculate through the reactors. The drained leachate inventories were re-circulated once per week.

A mass flow controller (Burkert 8710) was used to control airflow to the headspace of reactors at a rate of 3.32 L/min for 15 min on an hourly cycle. The headspace of the reactors was approximately 25 L, so this flow rate would have replaced 85% of the headspace gas every hour assuming mixed conditions in the headspace. The largest drawdown of O_2 concentration between headspace flushes was from an atmospheric level of 21% to 13%, 14.5%, 17.7% and 14% in R1, R2, R3 and R4 respectively. These levels are well above the O_2 scavenging level for composting organisms (Magalhaes et al., 1993; Miller, 1993). Air flow was switched from one reactor to the next by eight solenoid valves (Burket 0330), one on the inlet and outlet lines of each reactor. A data acquisition device (National Instruments cRIO-9074) programmed in LabVIEW was used to control of the solenoids and manage online data collection. The operating system also logged data from the upstream and downstream gas analyser sensors, the downstream gas flow meter and the thermocouple in each reactor. Two O_2 sensors, one CH_4 sensor and one CO_2 sensor (BlueSens, Inc., Germany) were used to measure the composition of the gas entering and leaving the headspace. All sensors were factory calibrated. The accuracy of the sensors was ±0.2%. The accuracy of the sensors was checked by performing weekly parallel gas chromatography analysis on gas samples using a Shimadzu G8A-FID for CH_4 and CO_2 (2 m packed Shincarbon ST column at 100/120 mesh; N_2 carrier gas; 140 and 390 °C for column and injector temperature respectively), and a Shimadzu G8A-TCD for O_2 (2.1 m long Molesieve 5A column at 80/100 mesh; Ar carrier gas; 60 and 150 °C for the column and injector temperature respectively). A wet flow meter (Shinagawa, Model WSDa-1A) equipped with a Shinagawa Uinics Preset (SUP) digital counter was used to measure the gas flow from each reactor. Fig. 1 shows the experiment set up. Fig. S1 in Supporting information showed more details on reactor set-up.

Table 1
Contents of reactors.

Parameters	R1	R2	R3	R4
Experimental design	Uncovered waste bed	Replicate of R1	Soil covered bed	Replicate of R1
Contents (wet kg MSW)	36.7 ± 0.5	29.7 ± 0.5	27.3 ± 0.5 with a layer of about 25 kg of silty loam soil	23.9 ± 0.5
Density (kg m^{-3})	218 ± 8	176 ± 6	162 ± 6	142 ± 5

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