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Greenhouse gas emissions from two-stage landfilling of municipal solid waste

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ABSTRACT

Simulations were conducted to investigate greenhouse gas emissions from aerobic pretreatment and subsequent landfilling. The flows in carbon balance, such as gas, leachate, and solid phases, were considered in the simulations. The total amount of CO_2 eq. decreased as organic removal efficiency (ORE) increased. At ORE values of 0, 0.30, 0.41, and 0.54, the total amounts of CO_2 eq. were 2614, 2326, 2075, and 1572 kg CO_2 eq. per one ton dry matter, respectively; gas accounted for the main contribution to the total amount. The reduction in CO_2 eq. from leachate was the primary positive contribution, accounting for 356%, 174%, and 100% of total reduction at ORE values of 0.30, 0.41, and 0.54, respectively. The CO_2 eq. from energy consumption was the negative contribution to total reduction, but this contribution is considerably lower than that from gas. Aerobic pretreatment shortened the lag time of biogas production by 74.1–97.0%, and facilitated the transfer of organic carbon in solid waste from uncontrolled biogas and highly polluting leachate to aerobically generated CO_2.

1. Introduction

Conventional landfilling is a commonly used method for the disposal of municipal solid waste (MSW). During waste degradation, a conservative percentage (50%) of the total carbon in MSW is released as landfill gas and leachate (Jeon et al., 2007); 90% of the degradable carbon in these pollutants is usually converted into CO_2 and CH_4 (Huber-Humer et al., 2011). CH_4 produced at solid waste landfill sites contributes approximately 12–18% of annual global anthropogenic methane emissions (Bogner et al., 2008; USEPA, 2006). Given that CH_4 is a powerful greenhouse gas, recovery of landfill gas through engineered systems can provide environmental and energy benefits by reducing surface emissions and by serving as an alternative energy source. The efficiency of landfill gas recovery largely depends on operating conditions. Park and Shin (2001) investigated the effects of forced extraction on landfill gas released from surface emission, and found that the extraction process can reduce fugitive landfill gas emissions from 30% to 6% of total generated emissions. Spokas et al. (2006) assessed CH_4 mass balance at three landfills with an active landfill gas recovery system. The authors found a gas recovery of 35% for an operating cell; 65% for a temporarily covered cell; 85% for a cell with a final clay cover; and 90% for a cell with a final geomembrane cover. Jung et al. (2011) estimated the effect of a high permeability layer on enhancing gas capture. Without a high permeability layer beneath the landfill cover, CH_4 emissions increased to as much as 24% of total generated CH_4, a value twice higher than that generated with a permeable layer installed.

In some parts of China, landfill gas is emitted directly to the atmosphere because of the lack of collection systems and control devices. Although an active gas recovery system is used, recovery efficiency is lower than 20% (Raninger et al., 2007) because of the unique characteristics of biogas produced by food waste. MSW in China typically contains a high amount of food waste, as well as minimal paper and other slowly degradable organics. In a landfill, biogas from food waste is generated at a considerably shorter time and faster rate than is biogas from paper. A high food content in waste also causes severe acid accumulation; leachate with a high COD concentration negatively affects the potential production of methane from MSW and contributes to the greenhouse effect. Up to 24.6% of organic carbon in MSW with 65% food waste was found released into leachate, whereas only 6.4% of organic carbon in MSW with 9.2% food waste released into leachate (Chen, 2010). Acid accumulation inhibits methane production and prolongs landfill stabilisation.

Aerobic pretreatment of MSW reduces waste mass and improves landfill processes. When the MSW that is disposed of in a landfill has been aerobically pretreated, leachate pollution load and biogas production potential are considerably diminished (Leikam and Stegmann, 1999; Zach et al., 2000; Kuruparan et al., 2003; Lornage et al., 2007; Mahar et al., 2009). However, the effect of aerobic pretreatment on greenhouse gas emissions during

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the entire two-stage landfilling has been rarely investigated. This study aims to estimate the effect of aerobic pretreatment on greenhouse gas emissions during two-stage landfilling and consequently reveal the role of aerobic pretreatment prior to landfilling. Three major issues were studied. First, carbon balance was observed to determine the characteristics of carbon flow. Second, cumulative gas production curves were predicted using a Gompertz mathematical model, from which gas generation rate can be effectively described. Third, the total amount of CO_2 and CH_4 emissions were observed, and the effect of aerobic pretreatment on the greenhouse effect caused by these pollutants are discussed to assess the greenhouse gas emissions from two-stage landfilling in China.

2. Materials and methods

2.1. MSW

A 500 kg MSW sample was obtained from a landfill in Beijing, China. The composition of the sample (Table 1) was determined by manual sorting. This sample is initial waste A0. The moisture (wet basis), volatile solid (VS), and total carbon contents of the sample were 64.5%, 65.1%, and 34.9%, respectively.

2.2. Column experiments

2.2.1. Aerobic pretreatment stage

A set of column experiments in which five reactors (R0–R4) were used, were performed for 0 d–50 d. The reactors, with an internal diameter of 500 mm and a height of 750 mm, are made of high-density polyethylene (Fig. 1).

Each reactor was filled with 77.5 kg (wet weight) of A0 at a height of 60 cm. After aerobic pretreatment, the wastes from R0–R4 were collected for detailed characteristic analysis and anaerobic experiments. The pretreated wastes from R0, R1, R2, R3, and R4 were labelled A0, A1, A2, A3, and A4, respectively. The aerobic operation modes and characteristics of wastes A1–A4 are described elsewhere (Zhang et al., 2012).

2.2.2. Anaerobic treatment stage

Wastes A0–A4 (wet mass, 0.12 kg–0.15 kg) were sampled and placed into five 500 mL flint glass solution bottles with rubber stoppers. The bottles were kept in a water bath at 37 °C. The rubber stopper had two holes for tube insertion. One tube was for air sampling, and the other was for measuring cumulative biogas, performed by discharging saturated salt water (Fig. 2). Before the experiment, the bottles were sealed and flushed with nitrogen for 1 min to ensure anaerobic conditions.

2.3. Methods

2.3.1. Analytical methods

Moisture content was determined by heating the ground sample to 105 °C for 24 h, and the results were expressed as wet basis. The VS content was determined by ashing the dry samples at 550 °C for 3 h in a muffle furnace. Wastes A0–A4 (about 10 kg wet mass each) were collected from R0–R4, dried to a constant weight at 105 °C, ground into fine powder with a vibration mill, and then used for elemental analysis. The total carbon in the sample was measured

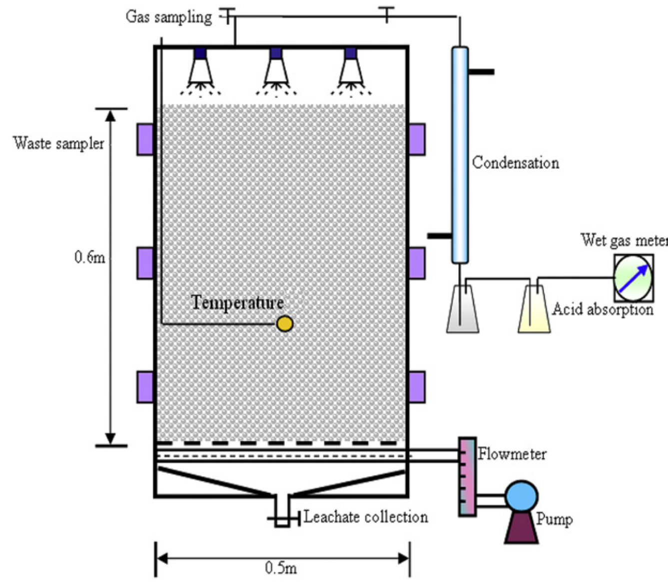

Fig. 1. Scheme of the reactor with changeable aerobic and anaerobic operation.

using a carbon-hydrogen-nitrogen analyser (Equipment CE 440; EAI USA). COD was measured using the potassium dichromate method. CO_2 and CH_4 were measured with a GA2000+ landfill gas analyser.

2.3.2. Definition of aerobic pretreatment

To depict the various two-stage landfilling processes, organic removal efficiency (ORE) is used to denote the end point of the aerobic pretreatment:

$$\mathrm{ORE} = \frac{\mathrm{VS_{initial}} - \mathrm{VS_{pretreated}}}{\mathrm{VS_{initial}}} \quad (1)$$

The ORE value of R0 was 0. The VS of A1–A4 decreased from an initial value 65.1%–49.6%, 45.2%, 38.2%, and 30.0%, respectively. The ORE values of R1–R4 were 0.23, 0.30, 0.41, and 0.54, respectively.

2.3.3. Carbon balance

Carbon balance is calculated to present the carbon flow through waste degradation using (2).

$$\mathrm{Carbon_{initial\ waste}} = \mathrm{Carbon_{leachate}} + \mathrm{Carbon_{gas}} + \mathrm{Carbon_{final\ waste}} + \mathrm{Carbon_{others}} \quad (2)$$

where $\mathrm{Carbon_{initial\ waste}}$ and $\mathrm{Carbon_{final\ waste}}$ are calculated from the measured masses and carbon concentrations by element analysis; $\mathrm{Carbon_{leachate}}$ is calculated from leachate volume and COD concentration using the TOC-to-COD ratio, 1/3 (Wang et al., 2008); $\mathrm{Carbon_{gas}}$ is calculated from gas volume and the volume percentage of CO_2 and CH_4, after which the formula $PV = nRT$ is used to obtain the mass carbon in biogas; and $\mathrm{Carbon_{others}}$ denotes the minor compositions of carbon, such as volatile organic compounds (VOCs), as well as the unavoidable carbon loss during the experiment. VOCs account for less than 1% (v/v) of typical landfill gases—hundreds of times smaller than carbon flux as CH_4 and CO_2.

Table 1
Composition of fresh MSW sample (w/w).

Components	Food waste	Paper	Textile	Wood	Plastic & rubber	Metal	Glass	Stone	Others
%	62.7	12.9	3.7	1.0	5.8	0.3	1.7	3.8	7.3