Waste Management 55 (2016) 83–92

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Biogas production enhancement using semi-aerobic pre-aeration in a hybrid bioreactor landfill

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ARTICLE INFO

Article history:
Received 4 August 2015
Revised 24 September 2015
Accepted 23 October 2015
Available online 31 October 2015

Keywords:
Landfill emissions
Landfill pre-aeration
Bioreactor landfill
Hybrid landfill
Methane production enhancement

ABSTRACT

Landfilling continues to be one of the main methods used in managing Municipal Solid Waste (MSW) worldwide, particularly in developing countries. Although in many countries national legislation aims to reduce this practice as much as possible, landfill is a necessary and unavoidable step in closing the material cycle. The need for innovative waste management techniques to improve landfill management and minimize the adverse environmental impact produced has resulted in an increasing interest in innovative systems capable of accelerating waste stabilization. Landfill bioreactors allow decomposition kinetics to be increased and post-operational phase to be shortened; in particular, hybrid bioreactors combine the benefits afforded by both aerobic and anaerobic processes. Six bioreactor simulators were used in the present study: four managed as hybrid, with an initial semi-aerobic phase and a second anaerobic phase, and two as anaerobic control bioreactors. The main goal of the first aerated phase is to reduce Volatile Fatty Acids (VFA) in order to increase pH and enhance methane production during the anaerobic phase; for this reason, air injection was stopped only when these parameters reached the optimum range for methanogenic bacteria.

Biogas and leachate were constantly monitored throughout the entire methanogenic phase with the aim of calibrating a Gompertz Model and evaluating the effects of pre-aeration on subsequent methane production. The results showed that moderate and intermittent pre-aeration produces a positive effect both on methane potential and in the kinetics of reaction.

1. Introduction

Landfilling continues to be one of the main methods used in managing Municipal Solid Waste (MSW) worldwide, particularly in developing countries. Although in many countries national legislation aims to reduce this practice as much as possible, landfill is a necessary and unavoidable step in closing the material cycle (Cossu, 2009). The need for innovative landfill management techniques to better minimize their adverse environmental impact, has led to an increasing interest in bioreactors, capable of accelerating the decomposition of MSW and reducing the post-operational phase of a landfill (Price et al., 2003; Raga and Cossu, 2013; Xu et al., 2014).

Bioreactor landfills are characterized by use of a series of technologies including water and/or air injection, leachate recirculation, and other combinations of in situ treatments to allow adjustment of pH, redox conditions and moisture content with the aim of creating a more suitable environment for degradation processes. Moisture control is required to support metabolic processes, transport of nutrients and microorganisms (Norbu et al., 2005), while air injection speeds up degradation processes (Cossu et al., 2003; Ritzkowski and Stegmann, 2013).

In recent years, it has been demonstrated that bioreactor landfill technology promotes the decomposition and stabilization of biodegradable organic waste, through water addition, leachate recirculation or air injection (Sun et al., 2013; Erses et al., 2008; Sekman et al., 2011; Sandip et al., 2012; Xu et al., 2014; Shao et al., 2008; He et al., 2011; Raga et al., 2015). In particular, as far as the metabolic pathway is concerned, three main types of landfill bioreactors are currently considered: anaerobic, aerobic and hybrid, the latter providing for a sequence of aerobic and anaerobic conditions (EPA, 2015). Most of the bioreactor landfills discussed in literature were operated under anaerobic conditions (Price et al., 2003; Valencia et al., 2011; Vigneron et al., 2007), causing ammonia accumulation and at times a partial or complete inhibition of methane production. On the contrary, a system operated solely under aerobic conditions may increase the degradation

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http://dx.doi.org/10.1016/j.wasman.2015.10.025
0956-053X/

kinetics of organic substances but inhibits completely methane generation and renders energy recovery impossible. Hybrid bioreactors operate under various combinations of aerobic and anaerobic conditions to achieve benefits from both (Long et al., 2009; Xu et al., 2014). The facultative landfills bioreactor is another type of Hybrid bioreactor which provides external aerobic pre-treatment of leachate prior to its recirculation in an anaerobic bioreactor, to allow both the nitrification and denitrification process to remove nitrogen compounds (De Abreu et al., 2005; US639895, 2002).

The test proposed in this study takes into consideration six landfill simulating bioreactors: four hybrid bioreactors with a first semi-aerobic phase prior to a second anaerobic phase and two anaerobic control bioreactors. During the semi-aerobic phase, air was injected into the waste mass to simulate natural convection caused by the temperature gradient between the external environment and the landfill body, with the goal of Volatile Fatty Acids (VFA) reduction and pH increase to enhance methane production in the next anaerobic phase. The effects of continuous and intermittent aeration were compared, the latter appearing beneficial for accelerating waste stabilization and reducing the acid formation, based on the outcomes of previous experiments (Sang et al., 2009). This hybrid system also provided for leachate recirculation to ensure better nutrient distribution and appropriate moisture content.

This test is based on S.An.A Landfill model (Semi-aerobic, Anaerobic, Aerated), a hybrid system featuring an initial semi-aerobic phase to enhance methane production occurring in the subsequent anaerobic step and, finally, forced aeration for the abatement of residual emissions (Repetti et al., 2013).

The change from semi-aerobic to anaerobic conditions was challenging: no aeration time was decided a priori, as this was highly dependent on the initial waste characteristics, but was selected with the aim of monitoring specific chemical parameters capable of guaranteeing optimal conditions for methanogenic bacteria.

The aim of the present study was to apply the hybrid waste management system, in order to combine the previously demonstrated advantages of leachate recirculation and aeration, with a greater methane production. In line with the mode of aeration and with air flow in each bioreactor at the moment of change from semi-aerobic to anaerobic operating conditions, an association with the characteristic parameters of methane generation (production rate, cumulative volume produced and lag phase) was observed. This analysis is of use in determining the optimum air injection method and airflow range to both stimulate methane production and increase degradation kinetics.

2. Materials and methods

2.1. Waste samples

The waste used for the experiment was the residual fraction of Municipal Solid Waste sampled after source segregation and provided by a public waste management company operating in thirteen municipalities of Livorno Province, Tuscany (Italy). A 200 kg sample was sieved with an 80 mm mesh and then analyzed by different waste fractions (Table 1); the undersieve (<80 mm fraction) was loaded into bioreactors. The waste composition was characterized by high amounts of food waste, plastic, paper and fines. Minor quantities of green waste, metals, glass, wood and textiles were detected (Table 1).

Table 1
Fractional composition of raw waste and undersieve (<80 mm), i.e. the fraction used to fill the reactors.

Trade class	Raw waste (%)	Undersieve <80 mm (%)
Food waste	14.0	17.4
Green waste	6.1	6.0
Paper	22.9	10.5
Plastic	18.4	12.6
Metal	5.2	6.2
Glass and inert	3.5	3.2
Wood	0.4	0.3
Textiles	8.5	5.1
Undersieve #20 mm	20.9	38.8

2.2. Equipment

The experiments were carried out by using six Plexiglass® (polymethyl methacrylate) columns (height 106 cm, diameter 24 cm). Each reactor was filled with the aim of reaching a density of 0.5 t/m^3, resulting in 18.4 kg MSW placed in each reactor. A 10-cm thick gravel layer (Ø 20–30 mm) was placed at the bottom and the top of each column as a drainage layer to facilitate the distribution of recirculated leachate (Fig. 1).

The upper end of reactor body was equipped with three valves providing for the introduction of air, sampling and extraction of gas as well as introduction of water and leachate recirculation. Recirculation was carried out from the top of the reactor using peristaltic pumps (Heidolph PD 5001). A leachate collection port was located at the bottom of each column for leachate extraction.

To channel air into the waste body, a vertical PVC pipe with side perforations was installed at the center of the waste layer; this system was designed to guarantee the uniform distribution of air throughout the reactor. The pumping equipment was a Prodac Air Professional pump 360 and inlet airflow was regulated by a Sho-Rate GT1135 flow meter. Biogas generated from each column was collected by a Tedlar® sampling bag connected to the upper gas port and its volume and quality were measured daily (Fig. 1).

Temperature monitoring was performed by means of Thermo Systems TS100 temperature probes installed inside the reactor and the temperature was maintained constant at 39–42 °C by means of a thermo-regulated insulation system covering all reactor lateral surfaces.

2.3. Methodology

The test was divided into three distinct main phases: Semi-aerobic, Anaerobic and Aerobic. The first phase was meant to enhance biogas production in the following anaerobic phase; the third one was functional to the complete stabilization of residual contaminants by means of aeration and flushing. In this paper, only the first two phases have been taken into consideration.

Six column reactors were filled with the same quantity of waste and managed under identical hydraulic conditions to obtain a clear comparison of results. Four reactors were Hybrid (IAa and IAb with intermittent aeration; CAa and CAb with continuous aeration); the remaining two were anaerobic (ANa and ANb) and used as control bioreactors. After filling and startup, aeration was commenced according to the scheme in Fig. 2, to simulate semi-aerobic conditions. Daily air flux was the same for all pre-aerated reactors (Fig. 2) and equal to 50 L/d at 20 °C, that in our specific case corresponds to 5 NL/d/kgTS, TS being the dry matter content (total solids) in the reactor. Intermittent aeration was turned on for twelve hours a day (4.1 L/h), while continuous aeration was provided all day long, seven days per week (2.1 L/h). Daily air flux was chosen on the basis of a series of lab-scale experiments carried out on landfill bioreactors in semi-aerobic conditions: these ranged from 0.7 NL/d/kgTS (Wu et al., 2014) to 32.0 NL/d/kgTS (Cossu et al., 2003) with average values between 4–10 NL/d/kgTS (Cossu