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Quantification of parameters influencing methane generation due to biodegradation of municipal solid waste in landfills and laboratory experiments

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A B S T R A C T

The energy conversion potential of municipal solid waste (MSW) disposed of in landfills remains largely untapped because of the slow and variable rate of biogas generation, delayed and inefficient biogas collection, leakage of biogas, and landfill practices and infrastructure that are not geared toward energy recovery. A database consisting of methane (CH_4) generation data, the major constituent of biogas, from 49 laboratory experiments and field monitoring data from 57 landfills was developed. Three CH_4 generation parameters, i.e., waste decay rate (k), CH_4 generation potential (L_0), and time until maximum CH_4 generation rate (t_{max}), were calculated for each dataset using U.S. EPA's Landfill Gas Emission Model (LandGEM). Factors influencing the derived parameters in laboratory experiments and landfills were investigated using multi-linear regression analysis. Total weight of waste (W) was correlated with biodegradation conditions through a ranked classification scheme. k increased with increasing percentage of readily biodegradable waste (B_{r0} (%)) and waste temperature, and reduced with increasing W, an indicator of less favorable biodegradation conditions. The values of k obtained in the laboratory were commonly significantly higher than those in landfills and those recommended by LandGEM. The mean value of L_0 was 98 and 88 L CH_4/kg waste for laboratory and field studies, respectively, but was significantly affected by waste composition with ranges from 10 to 300 L CH_4/kg. t_{max} increased with increasing percentage of biodegradable waste (B_0) and W. The values of t_{max} in landfills were higher than those in laboratory experiments or those based on LandGEM's recommended parameters. Enhancing biodegradation conditions in landfill cells has a greater impact on improving k and t_{max} than increasing B_0. Optimizing the B_0 and B_{r0} values of landfilled waste increases L_0 and reduces t_{max}.

1. Introduction

The generation rate and disposal demand of municipal solid waste (MSW) continue to increase whereas suitable sites for landfills are limited worldwide. Out of the 251 million tons of MSW generated in 2012 in the United States (U.S.), 54% was disposed of in landfills, 34% was recycled and 12% was incinerated (EPA, 2014b). Since the 1960s, more than 9 billion tons of MSW are estimated to have been generated and 6.7 billion tons have been disposed of in dumps or landfills. Although efforts are made to divert MSW from landfilling, the amount of MSW disposed of in landfills continues to increase (Fig. 1a). Since each alternative waste management options, i.e., recycling, incineration, anaerobic co-digestion with other waste streams, and composting, have their own technological and economical limitations, landfilling is expected to remain a major management option for MSW in the near future.

Under the prevailing anaerobic conditions in most landfills, biogas is produced during biodegradation of MSW. Landfill gas consists of approximately 40–60% methane (CH_4), 40–60% carbon dioxide (CO_2), and trace amounts of other gases (Barlaz et al., 1989; Pohland and Alyousfi, 1994). Modern landfills in the U.S. are regulated by Subtitle D of the Resource Conservation and Recovery Act, and are operated as "dry tombs" where the moisture content of waste is intended to remain low due to minimization of moisture infiltration (EPA, 2006). Even in bioreactor landfills or wet landfills that allow infiltration through permeable covers, moisture addition is often insufficient to allow for optimal biodegradation of the total weight of landfilled waste and moisture is often added intermittently and distributed unevenly (Benson et al., 2007; Bareither et al., 2010). As a result, MSW biodegradation

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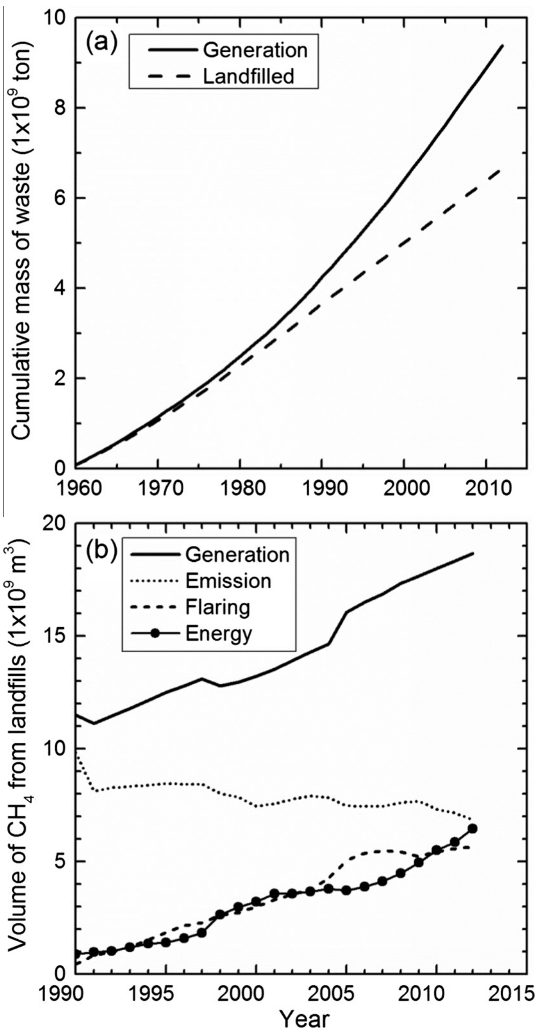

Fig. 1. (a) Cumulative mass of generated and landfilled waste with time; and (b) volume of CH_4 generated, emitted, flared and converted to energy in landfills with time (based on U.S. EPA's survey data (2014a)).

and biogas generation are much slower than under optimal conditions (Pohland and Kim, 2000; Reinhart et al., 2002). The rate of MSW biodegradation in landfills and the factors that influence the biodegradation process are significantly different from those in common anaerobic digestion systems, primarily because waste is a heterogeneous and porous material, and is under predominantly unsaturated conditions in landfills (Barlaz et al., 2010b).

The low biogas generation rate in landfills is a major barrier toward economical active collection of biogas and its conversion to usable energy, while the fluctuation in price of natural gas significantly affects commercial biogas recovery (EPA, 2010). In many landfills, biogas is collected passively through natural pressure gradient from degrading MSW and is flared for decades until MSW biodegradation and biogas generation stops (EPA, 2014a). Since energy recovery in landfills is currently not an explicit design objective, gas collection systems are not geared toward maximizing energy generation, but focus on regulation conformity which emphasizes emission minimization. The collection efficiency of biogas in modern landfills, with a gas collection system in place, is estimated to range between 35% and 90%. The remaining portion of biogas is either oxidized by methane-oxidizing bacteria present in cover soil or is leaked and emitted to the atmosphere (Spokas et al., 2006). In addition, gas collection systems are most commonly installed with some delay after waste placement. Thus, any CH_4 generated before a gas collection system is installed is lost.

Currently, out of 1754 landfills in the U.S., only 558 (32%) collect methane (EPA, 2010). Even in landfills where energy is recovered, design and management procedures are largely empirical leading to sub-optimal energy recovery and production. Although energy generation from landfill biogas has increased more than five times from 1989 to 2012 (Fig. 1b), MSW remains a largely untapped energy source. In 2012, the annual CH_4 generation from landfills in the U.S. was estimated to be 18.7×10^9 N m^3, of which only approximately 35% (6.5×10^9 N m^3 of CH_4) was converted into energy through combustion, another 30% (5.7×10^9 N m^3 of CH_4) was flared and released to the atmosphere as CO_2, and 35% remained uncaptured and was emitted to the atmosphere. The emitted CH_4 is estimated to be equivalent to 102.8×10^{12} g of CO_2 (CH_4 is considered to be at least 20 times more potent than CO_2 in terms of global warming potential (Solomon et al., 2007)) and responsible for approximately 21% of total anthropogenic CH_4 emissions in the U.S. (EPA, 2014a).

Besides the loss of potential energy and significant greenhouse gas emission due to slow MSW biodegradation in landfills, undegraded waste occupies more landfill space compared to biodegraded waste. Therefore, slow MSW biodegradation reduces the total waste disposal capacity of a landfill. The slowly biodegrading MSW also poses a long-term environmental threat as failure of the engineered containment systems of landfills will occur eventually exposing undegraded waste. For these reasons, the design philosophy and practices of modern landfills are not sustainable.

MSW biodegradation and biogas generation processes have been studied extensively in the laboratory and are commonly monitored in landfills. However, the availability, reliability and completeness of field monitoring data of landfills is often limited by labor, equipment, duration requirements, and cost (Wang et al., 2013). Biodegradation experiments of MSW conducted in the laboratory are better controlled and employ operating procedures to enhance microbial activity. Because of these reasons, laboratory experiments produce more reliable and predictable results compared to field monitoring studies.

This study presents a review of available MSW biodegradation data from laboratory experiments and field studies. The available data are synthesized with the intent to systematically identify similarities and differences between them. The CH_4 generation data of each dataset were fit using the U.S. EPA Landfill Gas Emission Model (LandGEM) (EPA, 2005). Three characteristic CH_4 generation parameters were obtained: waste decay rate (k, 1/yr), CH_4 generation potential of waste (L_0, L CH_4/kg), and time between waste placement and the maximum CH_4 generation rate (t_{max}, d). Relationships between initial waste composition, biodegradation conditions, and the CH_4 generation parameters were investigated and quantified based on the results of more than 100 laboratory experiments and field studies. Recommendations to improve operating practices that enhance energy harvesting from disposed waste in landfills are presented.

2. Methods and calculations

2.1. Literature review and classification of biodegradation conditions

Results of laboratory MSW biodegradation experiments and field monitoring data from landfills in the literature were reviewed. Around 200 available studies were first screened for completeness and resolution of time-dependent biogas generation data. From these, 45 studies were considered sufficiently comprehensive and were selected for further analysis. A database consisting of 49 laboratory experiments (Eleazer et al., 1997; Borglin et al.,