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Methane generation in tropical landfills: Simplified methods and field results

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ABSTRACT

This paper deals with the use of simplified methods to predict methane generation in tropical landfills. Methane recovery data obtained on site as part of a research program being carried out at the Metropolitan Landfill, Salvador, Brazil, is analyzed and used to obtain field methane generation over time. Laboratory data from MSW samples of different ages are presented and discussed; and simplified procedures to estimate the methane generation potential, L_o, and the constant related to the biodegradation rate, k are applied. The first order decay method is used to fit field and laboratory results. It is demonstrated that despite the assumptions and the simplicity of the adopted laboratory procedures, the values L_o and k obtained are very close to those measured in the field, thus making this kind of analysis very attractive for first approach purposes.

1. Introduction

The environmental impact of disposing all kinds of solid waste has been long recognized. Many strategies aimed to reduce production, to recycle and to re-use waste have been introduced in recent years. However, large amounts of waste must still be disposed in the environment; and as far as municipal solid waste (MSW) is concerned, the main alternative for its safe disposition continues to be the sanitary landfill.

A sanitary landfill is usually conceptualized as a biochemical reactor. In this giant reactor, waste and water are the main inputs, while gas and leachate are the major outputs. Landfill gas is the result of biological anaerobic decomposition of organic materials in landfills. The principal constituents present in landfill gas are methane (CH_4) and carbon dioxide (CO_2), but landfill gas is commonly saturated by water vapor and presents small quantities of non-methane organic components and various other trace compounds. In modern landfills, this gas is now usually collected or controlled to prevent its undesirable escape to the atmosphere or its movement through the surrounding soil. Sometimes the recovered gas is flared and nowadays there is increasing interest in using landfill gas to produce energy. In many of the issues related to this gas, determining its generation potential and rate is crucial as these are the most important parameters to size the gas collection and control system, the flaring system or the electric power plant, for example.

Some models have been introduced to estimate the methane and biogas generation rate of landfills. Among them, the first order decay model is generally recognized as being the most widely used approach as it is recommended by the US Environmental Protection Agency (USEPA, 1998, 2005) and by the Intergovernmental Panel on Climate Change (IPCC, 2006) for calculating methane emissions from landfills. In the USEPA version, the model rests on two basic parameters, L_o, the methane generation potential (m^3 CH_4/Mg of MSW) and k, the methane generation rate constant (yr^{-1}), while the IPCC version rests on decomposable degradable organic carbon, $DDOC_m$, instead of L_o.

Gas generation parameters can be obtained following different strategies, such as theoretical prediction, laboratory experiments and from best fit analysis of gas recovery in real landfills. Theoretical predictions based on the chemical composition of the waste would give absolute maximum methane potential. However, in practice this potential is never reached due to the inaccessibility of certain components and the inability of all organic waste to biodegrade. According to USEPA (2005), the theoretical methane potential must be adjusted by a biodegradability factor, also based on various assumptions. In laboratory experiments there are certain difficulties in reproducing the real conditions of landfilling, and gas measurement in pilot-scale cells and full-scale landfills usually represent the gas recovered, not the gas generated.

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Nomenclature

BF	biodegradable fraction
BF_W	biodegradable fraction of the waste as a whole
BMP	biochemical methane potential
C	cellulose
C_m	MSW organic matter methane generation potential
FR	component fraction in the waste composition, dry basis
H	hemicellulose
k	methane generation rate constant
L	lignin
LC	lignin content
L_o	methane generation potential
ms, mw and m	mass of waste solids, water and MSW total mass
MSW	municipal solid waste
Q	methane generation rate
q	specific methane generation rate
t	elapsed time
VS	volatile solids
w	water content (dry basis)
w_W	water content (wet basis)
$x(t)$	value of the variable x in the time t
$\sum Q$	cumulative methane production
D_x	finite variation of the generic variable "x"
DOC	degradable organic carbon
$DDOC_m$	decomposable degradable organic carbon
DOC_f	fraction of DOC that decomposes under anaerobic conditions
MCF	methane correction factor

Strategies for obtaining gas generation parameters are suggested by the USEPA (2005) and by the IPCC (2006), including default values. Although the models and parameters have improved in recent years, it is recognized that current methods are not totally infallible (USEPA, 2005) and a full model would be very complex and site-dependent (IPCC, 2006). In this sense, continuing improvement of current models, especially in the topic of parameters prediction, acquisition and validation, is a topic of concern. In addition, if simplified procedures of parameters estimation were available they could be useful to ease the workload of obtaining parameters for preliminary purposes and for countries where the access to specialized expertise is not easy.

2. Fundamentals of biogas generation

Many factors interfere in the generation of methane in a landfill, but the most important factors include the waste composition and the presence of readily degradable organic components, the moisture content, the age of the residue, the pH and temperature. The pH and the temperature are relevant for the existence and action of bacteria (McBean et al., 1995) and they influence the type of bacteria that predominate and the rate of gas generation. According to Mehta et al. (2002) and Barlaz et al. (1990), the moisture content is a parameter that controls methane generation, since it stimulates microbial activity by providing better contact between soluble and insoluble substrates and microorganisms.

As regards the waste composition, different waste components will degrade at different rates over time. The readily degradable components normally include food waste and a portion of green waste (grass). The moderately decomposable components include a portion of the paper waste and the remaining green waste, and the slowly degradable part includes the remaining portion of the paper waste (newsprint and coated paper), wood, textiles, and other materials. Plastic, glass, metal, concrete, rubble, and other inert materials are normally considered non-biodegradable.

MSW is made up of organic and inorganic materials. The organic portion, that typically contains 40–50% cellulose, 10–15% lignin, 12% hemicellulose and 4% protein in dry weight is the part that can be converted into methane through physical–chemical and biological phenomena (Barlaz et al., 1989). This conversion is well-documented in literature and can be found in detail in Farquhar and Rovers (1973), Pohland (1975), Tchobanoglous et al. (1993) and Barlaz et al. (1997). In anaerobic conditions the degradation rates of the cellulose and lignin vary considerably; while the cellulose content clearly decreases during the waste degradation process, the lignin content increases notably because the lignin is highly recalcitrant and stable under anaerobic conditions (Bookter and Ham, 1982). According to Barlaz et al. (1989), in a laboratory-scale simulation only around 70–75% of the initial cellulose and hemicellulose was converted into gas.

These differences in the rate of depletion have led to the use of ratios between the contents of cellulose and lignin (C/L) and cellulose plus hemicellulose and lignin (degree of lignification = (C + H)/L) to identify the state of decomposition of the organic components. Additionally, the volatile solids content (VS) has been used to express total organic matter still present in the waste (Barlaz et al., 1997; Mehta et al., 2002). According to Mehta et al. (2002) and Röhrs et al. (2003), the VS is a good parameter to indicate the loss of organic material from a landfill over time; however, alone it is not a good indicator of the remaining gas potential because not all the volatile material is converted into gas, as is the case of plastics and rubber. Röhrs et al. (2003) suggest that an estimate of the remaining degradable organic matter can be obtained by measuring the cellulose content of samples or correcting (reducing) the VS by the portion of non-degradable or recalcitrant matter. The same principle was used by Tchobanoglous et al. (1993), who proposed using the lignin content to determine the biodegradable fraction of volatile solids.

3. Simplified approaches to estimate methane generation potential

According to Lobo (2003), the biodegradable portion (BF) of the waste or the value of BF concerning a specific waste component can be obtained through tests that quantify the biochemical methane potential (BMP). The BF value can be calculated using the ratio between the BMP value and the values predicted by stoichiometric equations (here called C_m), which assumes a complete conversion of organic matter to gaseous products.

The C_m values vary according to the component considered, but they are normally between 400 and 500 L CH_4/dry-kg. According to Barlaz et al. (1990), values of C_m of 414.8 and 424.2 L CH_4/dry-kg can be considered for cellulose and hemicellulose, respectively. Tchobanoglous et al. (1993) present biogas generation potential from 750 to 900 L biogas/dry-kg. As the biogas methane fraction usually varies from 0.5 to 0.6, similar values of C_m are predicted by the authors. Table 1, reproduced from Lobo (2003), presents the BF values for different components of waste suggested by several authors.

Table 2 presents values of C_m predict by Eq. (1) (Tchobanoglous et al., 1993) for different waste components. Values of C_m for the waste as a whole can be calculated using the waste composition (dry basis) and the values of BF values suggested by Lobo (2003),

Table 1
BF values suggested in the technical literature

Author	BF					
	Paper	Cardboard	Food waste	Garden waste	Wood	Textiles
Tchobanoglous et al. (1993) and Bonori et al. (2001)	0.44	0.38	0.58	0.45	0.61	0.40
Barlaz et al. (1997)	0.19–0.56	0.39	0.70	0.70–0.34	0.14	–
Harries et al. (2001)	0.30–0.40	0.44	–	0.20–0.51	0.30–0.33	0.17–0.25
Lobo (2003) – adopted	0.40	0.41	0.64	0.35	0.17	0.32

Modified from Lobo (2003).

Table 2
Methane generation (C_m) and water consumption according to Eq. (1)

Waste organic component	C_m (m^3 CH_4/dry-Mg)	H_2O consumption (H_2O kg/dry-kg)
Food wastes	505.01	0.26
Paper	418.51	0.20
Cardboard	438.70	0.16
Textiles	573.87	0.41
Leather	759.58	0.64
Yard wastes	481.72	0.28
Wood	484.94	0.24

$$C_aH_bO_cN_d + \frac{[4a - b - 2c + 3d]\cdot H_2O}{4} \rightarrow \frac{[4a + b - 2c - 3d]\cdot CH_4}{8} + \frac{[4a - b + 2c + 3d]\cdot CO_2}{8} + d\cdot NH_3 \quad (1)$$

Following the concepts presented above, if the biodegradable fraction of the waste as a whole, BF_W, and the value of C_m are known, the waste methane generation potential, L_o, can be easily calculated. Eq. (2) can be used to calculate BF_W. The fraction (dry basis) of each component in the waste composition, FR, is multiplied by its BF value, and the value of BF_W is calculated by adding the components considered. The waste average value of C_m can be calculated using Eq. (3),

$$BF_W = \sum_{i=1}^{n} BF_i \cdot FR_i \quad (2)$$

$$C_m = \frac{\sum_{i=1}^{n} BF_i \cdot FR_i \cdot C_{mi}}{BF_W} \quad (3)$$

Once the BF_W and C_m values are known, Eq. (4) can be used to calculate L_o. The water content, w, is used to consider only the dry mass of potentially degradable organic matter,

$$L_o = \frac{BF_W \cdot C_m}{1 + w} \quad (4)$$

IPCC (2006) presents another simplified model in which the methane generation potential is estimated through a mass balance approach that involves the determination of the degradable organic carbon (DOC) content of the waste. One key input in the model is the amount of degradable organic matter (DOC_m) in waste disposed into landfill. In the case of municipal solid waste, this is estimated using information on the different waste types/materials (food, paper, wood, textiles, etc.) included in the MSW composition.

The equations for estimating the CH_4 generation potential are given below. They were slightly modified to better fit the context of this paper. The basis for the calculation is the amount (here given in mass fraction, dry basis) of decomposable degradable organic carbon ($DDOC_m$) as defined in Eq. (5). $DDOC_m$ is the part of the organic carbon that will degrade under the anaerobic conditions. $DDOC_m$ equals the product of the fraction of degradable organic carbon in the waste (DOC), the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOC_f), and the portion of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in the landfill, which is interpreted with the methane correction factor (MCF),

$$DDOC_m = DOC \cdot DOC_f \cdot MCF \quad (5)$$

Eq. (6) may be used to calculate the $DDOC_m$ value of the waste as a whole considering data presented in Table 3 (IPCC, 2006) for different waste components and the waste composition (dry basis). FR is the fraction (dry basis) of each component in the waste composition. Table 4 presents suggested values for MCF according to the type of landfill,

$$DDOC_m = MCF \cdot \sum_{i=1}^{n} DOC_i \cdot FR_i \cdot DOC_{f_i} \quad (6)$$

Comparing the two approaches presented here, it may be said that DOC_f and BF have a similar meaning and that DOC and BMP are closely related.

DOC_f is an estimate of the fraction of carbon that is ultimately degraded and released from landfill, and reflects the fact that some degradable organic carbon does not degrade, or degrades very slowly under anaerobic conditions. DOC_f is usually assumed as 0.5 (on the assumption that the landfill environment is anaerobic and the DOC values include lignin). DOC_f value (as BF) is dependent on many factors such as temperature, moisture, pH, composition of waste, etc. As suggested in Eq. (6), DOC_f may be estimated for each waste component taking into account the waste composition in the predicted methane generation value.

In the IPCC (2006) model, the methane generation potential, L_o (m^3 CH_4/Mg of MSW), may be calculated using Eq. (7) below. F_{CH_4} is the CH_4 volume concentration in the gas, 16/12 is the molecular weight ratio of CH_4 and C and ρ_{CH4} is the methane density, which may be adopted as 0.717 kg/m^3 for practical purposes. Field values of F_{CH4} are around 0.55; w is the wastewater content, dry basis,

$$L_o = \frac{DDOC_m \cdot F_{CH_4} \cdot \frac{16}{12}}{\rho_{CH_4} \cdot (1 + w)} \quad (7)$$

Both the USEPA (1996) and the IPCC (2006) consider that the methane generation rate decays exponentially with time (Eq. (8)). In this equation, q is the specific methane generation rate (m^3 CH_4 /yr Mg of MSW), k is the methane generation rate constant (yr^{-1}) and t is the time since waste disposal (yr),

$$q = L_o \cdot k \cdot e^{-k\cdot t} \quad (8)$$

According to the USEPA (1998), the values of L_o vary widely; between 6.2 and 270 m^3 CH_4/Mg of MSW. Developing countries often present higher values of L_o. It must be emphasized, however, that in tropical developing countries the elevated values of water content tend to reduce the dry matter content of the waste, counterbalancing the presence of high contents of organic matter. The k values (around 0.2 yr^{-1}) are associated with high temperatures and moisture contents and to the presence of large amounts of food waste.

Table 3
Values of DOC and dry matter content suggested by IPCC (2006)

MSW component	Dry matter content in % of wet weight	DOC content in % of wet waste		DOC content in % of dry waste	
	Default	Default	Range	Default	Range
Paper/cardboard	90	40	36–45	44	40–50
Textiles	80	24	20–40	30	25–50
Food waste	40	15	8–20	38	20–50
Wood	85	43	39–46	50	46–54
Garden and park waste	40	20	18–22	49	45–55
Nappies	40	24	18–32	60	44–80
Rubber and leather	84	39	39	47	47
Plastics	100	–	–	–	–
Metal	100	–	–	–	–
Glass	100	–	–	–	–
Other, inert waste	90	–	–	–	–

Table 4
Values of MCF suggested by IPCC (2006)

Type of Site	MCF default values
Managed – anaerobic	1.0
Managed – semi-aerobic	0.5
Unmanaged – deep (>5 m waste) and /or high water table	0.8
Unmanaged – shallow (<5 m waste)	0.4
Uncategorized landfill	0.6

Values of k of about 0.03 yr^{-1} are associated with cold and dry environments.

According to the IPCC (2006), the value of k (and consequently the waste half-life, $t1/2$) is affected by a wide variety of factors related to the composition of the waste, climatic conditions at the site where the landfill is located, characteristics of the landfill, waste disposal practices and others. The half-life value ($k = \ln(2)/t1/2$) applicable to any single landfill is determined by a large number of factors associated with the composition of the waste and the conditions at the site. The most rapid rates (k = 0.2 yr^{-1}, or a half-life of about 3 yr) are associated with high moisture conditions and rapidly degradable material such as food waste. The slower decay rates (k = 0.02 yr^{-1}, or a half-life of about 35 yr) are associated with dry site conditions and slowly degradable waste such as wood or paper. A half-life of less than 3 yr may be appropriate for managed landfills in a wet, temperate climate or rapidly degrading waste in a wet, tropical climate. The authors believe this is the case of the Metropolitan Center Landfill, located in the city of Salvador, Bahia, Brazil, the coordinates of which are 12°52′34.8″S; 38°21′46.7″W. Table 5 shows some k values suggested by the IPCC (2006).

This paper presents field results of methane generation rates and uses the first order decay method in order to obtain L_o and k values. Laboratory results of waste characterization tests are analyzed, and simplified procedures are used to predict L_o and k values based on data obtained from waste samples of varying ages.

4. Materials and methods

This section describes the procedures adopted to acquire the key parameters of the waste, which are then used to predict the methane generation potential of the waste samples as well as obtain and analyze the gas generation rates in the field.

4.1. Waste characterization

Sampling – As MSW is made up of many components of varied sizes, acquiring samples of good quality (representative of the waste stocked in the landfill) is a task that must be carried out very carefully. Samples of new waste were always collected on the same day of the week, normally from four trucks chosen randomly in the disposal front. About 200 kg of waste was collected from each truck. The samples of waste were placed over a HDPE blanket and the plastic bags were opened to allow better homogenization. Manual and machine assisted homogenization and quartering was performed until representative samples of waste were acquired. A sample containing about 100 kg of waste was used in the characterization tests and another sample, of about 20 kg, was used to determine the water content of the waste in its natural state. The collected samples were then placed in containers and sealed appropriately to prevent moisture variation. In the case of the samples collected from inside the waste body of the landfill, no quartering was used and the age of the samples (1 and 4 yr) was estimated using the landfill inbound waste control.

Waste composition – Waste composition, wet basis, was determined just after sampling in a field laboratory using some basic tools (oven, balance, trays, masks, gloves, plastic sacks, etc.). Waste components were separated into the following groups: paper/cardboard, plastic, rubber, metal, wood, glass, ceramic materials/stone, textiles and paste fraction. The paste fraction includes organic materials which are easily degradable (food waste), moderately degradable (e.g., leaves) and other materials not easily identifiable. After separation, each component was promptly stored in sealed plastic bags and weighed. Waste composition, dry basis, was determined after drying at 70 °C (samples were weighed each 24 h and removed from the oven after the observation of steady state conditions). This procedure allowed determination of the waste composition on dry and wet bases and the water content of each component.

Water content – Values of water content on a dry basis (w = mw/ms) and wet basis (w_W = mw/m) were determined for each component and for the waste as a whole. The terms mw, ms and m refer to the masses of water, solids and total, respectively. The water content of the waste as a whole was obtained using: (a) the waste dry composition and the individual values of the water content of each component, and (b) the samples of waste in its natural state. These values were used to check the efficacy of the measures taken in order to avoid water loss from the samples. In this paper the terms water content and waste composition will always refer to dry basis, except when otherwise indicated.

Table 5
Values of k suggested by IPCC (2006)

Type of waste		Dry boreal and temperate climate		Wet boreal and temperate climate		Dry tropical climate		Wet tropical climate	
		Default	Range	Default	Range	Default	Range	Default	Range
Slowly degrading waste	Paper/textiles waste	0.04	0.03–0.05	0.06	0.05–0.07	0.045	0.04–0.06	0.070	0.06–0.085
	Wood/straw waste	0.02	0.01–0.03	0.03	0.02–0.04	0.025	0.02–0.04	0.035	0.03–0.05
Moderately degrading waste	Other (non-food) organic putrescible/garden and park waste	0.05	0.04–0.06	0.1	0.06–0.1	0.065	0.05–0.08	0.170	0.15–0.2
Rapidly degrading waste	Food waste/sewage sludge	0.06	0.05–0.08	0.185	0.1–0.2	0.085	0.07–0.1	0.400	0.17–0.7
Bulk waste		0.05	0.04–0.06	0.090	0.08–0.1	0.065	0.05–0.08	0.170	0.15–0.2

Volatile solids content – The VS of the paste fraction was obtained after waste sieving. The paste fraction was quartered to a mass value of about 1000 g and ground to reduce the size of particles and to increase the specific surface. Paste samples containing about 20 g were placed into crucibles and dried in an oven at 70 °C for 1 h. Samples were combusted in muffle at 600 °C for 2 h. After that, VS values were computed using the ratio between the loss of mass and the dry mass before combustion.

Lignin content – The lignin content (LC) of the paste fraction was determined using a gravimetric method similar to that proposed by Hatfield et al. (1994). Two-stage acid hydrolysis was used. Samples containing about 3 g of the same material used for VS determination were used. After washing with 150 ml of a 2:1 solution of toluene and 95% ethanol for 1 h to remove lipids, the samples were filtered and the remaining solids underwent primary hydrolysis using 150 ml of 72% sulfuric acid (H_2SO_4). The secondary hydrolysis was carried out using a 28-fold dilution. LC values were calculated using the remaining solids and the same procedure adopted as in the VS determination. The loss of mass by combustion after washing and hydrolysis is totally attributed to lignin, since this process supposedly removes only cellulose and hemicellulose.

Although not intrinsically linked to prediction of gas generation, any waste characterization procedure should include the determination of other key features, such as waste granulometric curve, specific weights, void ratios, etc. Such tests were carried out on the waste samples collected, and the results can be found in Machado et al. (2006a,b).

4.2. Waste characterization – complementary campaign

In order to better estimate the remaining methane generation potential over time, a complementary sampling campaign was performed, involving non-fresh waste of different ages. In this case waste components were separated into the following groups: paper/cardboard, wood, paste fraction and others (not easily degradable material). All the other procedures remained as described above. The age of the collected samples was estimated at 3.92, 4.42, 5.50, 7.84, 8.76 and 9.09 yr.

4.3. Landfill methane recovery and generation rates

The Metropolitan Center Landfill (MCL), located on the outskirts of the city of Salvador, Brazil, started its operation in October 1997 receiving only part of the city's waste. From March 1999 the landfill started receiving all the waste generated in Salvador and towns located in the vicinity. Incoming waste rates are subject to seasonal oscillations, as can be seen in Fig. 1 showing the average daily rates of incoming waste for each month. There are peak values in the period December–March. These values are probably associated with the influx of tourists in the summer season. If seasonal variations are taken into account, it can be said that since March 1999 the rate of incoming waste has remained almost constant over time. To date, around 2300 Mg of waste are disposed of daily in this landfill.

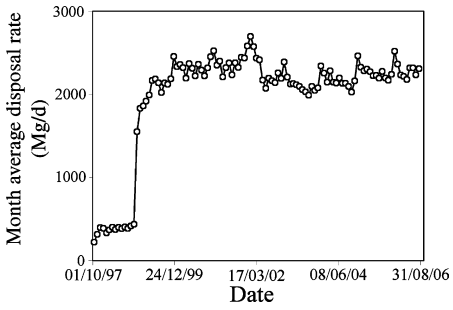

Fig. 1. MSW disposal rate at the Metropolitan Center Landfill.

The bottom of the MCL cells is located 6–12 m below the soil surface, and the thickness of the waste column at the end of the disposal process reaches about 45 m. A double liner system is used at the bottom and on the lateral slopes of the trench (1 m clay liner, $k < 1 \times 10^{-7}$ cm/s plus 2 mm HDPE membrane). Temporary covers are made using a single layer of soil $k < 1 \times 10^{-5}$ cm/s, 60 cm thick. These layers are removed in the case of additional disposal. Final covers use a PVC-geotextile membrane (PVC-GM) over the soil layer (60 cm thick) and about 20 cm of organic soil for grass support, which is located over the PVC-GM. Up to now around 25 ha have been used for waste landfilling.

A biogas recovery system was installed at the end of 2003 as part of the Landfill's Clean Development Mechanism. To date this system is composed of almost 200 superficial and deep gas drains. Deep gas drain construction normally follows the landfilling process, and the drains connect the bottom to the cover layers of the landfill. There are, however, additional deep drains that are installed after the final cover, using boring machines. In this case the depths are about 20 m.

Superficial drains are located above the soil layer of the final cover and beneath the PVC-GM (Fig. 2) and serve to collect the biogas accumulated in this region and to minimize possible fugitive emissions due to PVC-GM non-conformities. Individual measurements of gas flow rate, temperature and composition are made monthly in all the drains of the landfill. The gas recovery system is composed of a control center, where measurements of temperature, composition and recovery rates are made considering the

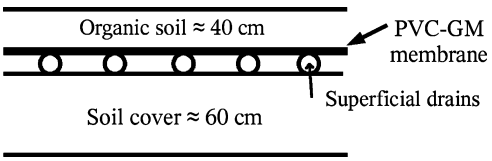

Fig. 2. Schematic view of the final cover adopted in the MCL.

Table 6
Values of gas recovery rates and related values of total, covered and exposed areas

Date	Recovery rate (m^3 CH_4/h)	Number of deep drains	Number of superficial drains	Total area (m^2)	Covered area (m^2)	Exposed area (m^2)
July 2004	3050	68	10	208,415	88,063	120,352
Aug 2004	3150	42	7	208,415	88,063	120,352
Nov 2004	2757	73	7	208,415	88,063	120,352
Mar 2005	4396	59	12	230,898	105,225	125,673
Apr 2005	4770	75	20	230,898	156,823	74,075
May 2005	4780	73	20	230,898	156,823	74,075
June 2005	4653	69	21	230,898	156,823	74,075
Aug 2005	4637	87	17	230,898	156,823	74,075

Table 7
Deep and superficial drains recovery rates and estimated values of fugitive emissions

Date	Recovery rate, deep drains (m^3 CH_4/h)	Recovery rate, superficial drains (m^3 CH_4/h)	Estimated fugitive emission (m^3 CH_4/h)	Average depression (mm Hg)
July 2004	2584.49	465.51	749	8
Aug 2004	2777.03	372.97	907	14
Nov 2004	2587.48	169.52	663	4.75
Mar 2005	3974.42	421.58	236	22.9
Apr 2005	4047.16	722.84	357	26.2
May 2005	4252.48	527.52	303	21.1
June 2005	3924.58	728.42	308	31.7
Aug 2005	4162.59	474.41	240	30.5

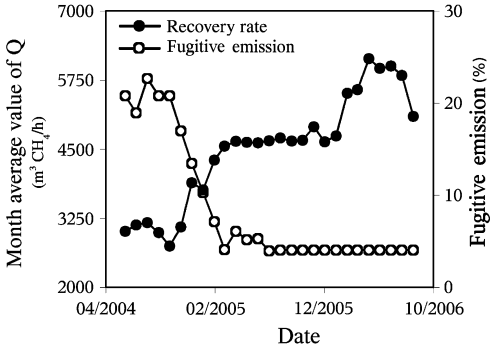

Fig. 3. Methane recovery rates and fugitive emissions.

system as a whole, three flares, gas humidity removers and a set of pumps responsible for applying suction to all the installed drains, forcing gas extraction. Tables 6 and 7 illustrate some values obtained in the gas measurement campaigns performed monthly. In Table 6 values of recovery rates, number of deep and superficial drains and the evolution of the total, covered and exposed landfill areas are presented.

In this paper, covered area refers to the area where the final cover is already installed (use of the PVC-GM and superficial drains). Exposed area refers to the areas where temporary covers are used and those without any cover installed (disposal front). Table 7 shows the contribution of the deep and superficial drains to the recovery rate. As can be seen, superficial drains are responsible for recovery rates that are 7–19% of the recovery rates obtained in the deep drains. These values vary according to a large number of parameters (relative number of drains, values of applied depression by the recovery system, water content of the soil cover layer in the exposed areas, etc.), and the influence of each variable in the obtained results is not easily assessed (Britto, 2006). Values of specific methane generation rate (L CH_4/m^2 h) obtained using the superficial drains were used to estimate fugitive emissions in the exposed area over time. Since August 2005 the PVC-GM has also been used as a temporary cover and exposed areas are kept to a minimum (less than 3000 m^2). Fig. 3 presents the average rates of methane recovery for each month and the estimated values of fugitive emissions. As can be seen, the methane recovery rate increases from 3013 m^3 CH_4/h in June 2004 to 5095 m^3 CH_4/h in August 2006. Fugitive emissions decreased from about 21% to 5% of the total generated over the same period.

4.4. Predicting landfill methane generation rates from waste characterization data

This section presents the method used to estimate $L_o(t)$ and k values from waste characterization data. The waste composition of new samples was used to estimate the methane generation potential and samples of waste of varying ages were used to determine the value of the methane generation rate, k.

The MSW methane generation potential of new samples of waste was calculated using the Eqs. (2)–(8) presented above. In the case of samples of varying ages, Eq. (9) was used to predict the remaining waste biodegradable fraction, $BF_W(t)$. As can be seen, the ratio between the volatile solids content at some instant, $VS(t)$, and the initial value of VS, VS_0, was used to correct the biodegradable fraction of each component over time. The use of Eq. (9) is very important to correct the BF values of the paste fraction due to the difficult separation of certain waste components (fine grained material, changes in the original features of the waste components) common after some years since disposal. The associated values of the remaining methane generation potential, $L_o(t)$, were obtained also by using Eq. (4), replacing BF_W with $BF_W(t)$. VS values in Eq. (9) must exclude plastic and rubber content. The same correction used in Eq. (9) may be used to correct C_m values for samples of varying ages,

$$BF_W(t) = \sum_{i=1}^{n} BF_i \cdot FR_i \cdot \left[\frac{VS(t)}{VS_0}\right]_i \quad (9)$$

The first order decay model (Eq. (8)) was used to calculate the value of k. Eq. (10) presents a more straightforward way of using the values of L_o concerning samples of varying ages to calculate k,

$$\frac{L_o(t)}{L_o} = e^{-k \cdot t} \quad (10)$$

In the case of the IPCC (2006) method, Eq. (11) was used, replacing Eq. (9),

$$DDOC_m(t) = MCF \cdot \sum_{i=1}^{n} DOC_i \cdot FR_i \cdot DOC_{f_i} \cdot \left[\frac{VS(t)}{VS_0}\right]_i \quad (11)$$

Values of MCF = 1 and $F_{CH_4} = 0.6$ were adopted. In order to better compare the obtained results, DOC_f values were assumed equal to BF for each waste component (see Table 1). This approach takes into account that older samples which have smaller contents of food and garden waste in comparison with new ones tend to have lower BF (or DOC_f) values.

4.5. Using the estimated landfill methane generation data to obtain L_o and k

The values of methane generation calculated as described above were used to estimate L_o and k field values. The first order decay model was used to fit the field values of methane generation (methane recovery + fugitive emissions). To minimize the effects of the variations observed on site in the incoming waste, methane recovery rates and fugitive emissions, the cumulative methane generation was used to obtain the values of L_o and k that better reproduce behavior on site. Eqs. (12) and (13) were used in data fitting. They are more appropriate for data analysis and represent Eq. (8) incrementally. In Eq. (12), t is the average time since waste dis-

posal (yr) and Δm is the amount of waste stocked each month (Mg). Q is the methane generation rate estimated (m^3 CH_4/yr) for each month. In Eq. (13), $\sum Q$ is the accumulated generation of methane (m^3 CH_4) and Δt_j is time period of the month considered (yr).

$$Q_j = \sum_{i=1}^{n} L_o \cdot k \cdot e^{-k \cdot t_i} \cdot \Delta m_i \quad (12)$$

$$\sum Q = \sum_{j=1}^{n} Q_j \cdot \Delta t_j \quad (13)$$

5. Results and analysis

5.1. Laboratory results

Tables 8 and 9 present the obtained water content results. Table 8 presents water content results considering the waste as a whole. Water content values obtained using the waste in its natural state (without waste segregation) and the individual values of water content of each component after waste separation presented less than 20% difference, with the exception of the samples NW09/05 and 8.76 yr old, indicating that the loss of water during component separation was small in most cases. The water content (wet basis) results presented in Table 8 are derived from those obtained considering the waste in its natural state. Values of w obtained using samples collected from inside the waste body were normally smaller (except for the value of w = 176% obtained for 1 yr old sample). The obtained values for water content are close those obtained by Carvalho (1999) from the MSW from Bandeirantes Landfill, Brazil, and those published by Gabr and Valero (1995), Landva and Clark (1990) and Coumoulos et al. (1995).

Values of water content for each waste component (samples of new waste) are shown in Table 9. Despite the great variation in the values, it can be said that glass, stones/ceramics, metal and rubber presented the lowest moisture values, due to their lower capacity for water absorption. Textiles, paper/cardboard and paste fraction present the highest values. Paste fraction presents an average value of w = 136% with values varying between 112% and 162%. The highest values of water content of the paste fraction were obtained for samples NW03/06 and NW01/04 (w = 144% and w = 162%, respectively) and they are related to periods of heavy rain. Table 10 uses the data presented in Table 9 and makes a comparison with the values of dry matter content suggested by the IPCC (2006) and presented in Table 3. The paste component is composed of food and garden waste. It can be noted that the obtained values of dry matter content are always smaller than ones suggested by the IPCC (2006). The greater discrepancies are found in the components, paper/cardboard, textiles, wood and plastics. It is believed that in the case of tropical wet climates, these components are able to retain a significant amount of water that becomes free water (leachate) after landfilling.

Table 11 shows the waste composition of samples of varying ages. Average values are presented for samples of new waste. Significant variations in the contents of paper/cardboard, metal, plastic and paste fraction can be observed. As can be noted, the expected decrease in the paste content over time is not clear. This is probably due to the fact that as the decomposition process continues, several waste components and even soil from temporary covers are incorporated into the paste fraction due to their difficult separation. The organic matter content of the paste (FR times VS), however, decreases with the time (as expected). Paste VS values between 47% and 65% were found in samples of new waste, with an average value of 57.9%. In the case of the 9 yr old sample, this value decreases to 16.19%. When the organic matter content of the paste is analyzed, a decrease from 20.8% to 5.25% in 9 yr can be seen. An average content of lignin of 13% in paste was obtained for new samples of waste. This value is lower than that found by Barlaz et al. (1997) for MSW as a whole: 23.1%. The same authors, however, identified a value of about 10.5% for food waste, the most important component of the paste in the new samples.

Values of C_m, BF_W, $DDOC_m$ and L_o obtained using the procedures described above are shown in Table 12. A value of w = 91%, the same obtained for new samples of waste, was adopted for all the waste samples. This was done to eliminate the influence of water infiltration, waste compression, etc. in the values of water content of the samples collected inside the landfill. An average value of L_o = 65.9 m^3 CH_4/Mg MSW was obtained considering the samples of new waste and the use of C_m and BF_W. This value decreases to L_o = 19.73 m^3 CH_4/Mg MSW when the 9 yr old sample is

Table 8
Moisture content of the waste studied

Samples	Moisture content – dry basis (%)		Moisture content – wet basis (%)
	Waste as collected	After component separation	
NW01/04[a]	83.1	101.1	50.3
NW09/04	75.0	84.1	45.7
NW03/05	70.8	83.0	45.4
NW09/05	122.4	83.8	45.6
NW03/06	113.7	103.9	50.9
Average new waste	93.0	91.2	47.6
1 yr old	176.1	–	63.8
4 yr old	91.2	–	47.4
8.76 yr old	69.46	39.21	40.97
7.84 yr old	70.12	65.98	41.22
5.50 yr old	70.27	77.39	41.27
9.09 yr old	63.70	68.84	38.91
3.92 yr old	57.06	63.92	36.33
4.42 yr old	85.22	79.71	46.01

[a] NW01/01 – new waste month and year of sampling.

Table 9
Moisture content in dry basis for each component of samples of new waste

Components	Moisture content – dry basis (%)					
	NW01/04	NW09/04	NW03/05	NW09/05	NW03/06	Average
Wood	44.4	73.8	41.5	61.6	60.1	56.3
Stone/ceramic	13.0	17.8	9.4	10.7	12.0	12.6
Textiles	121.6	100.6	119.3	123.6	98.8	112.8
Rubber	62.5	13.8	11.8	2.5	16.9	21.5
Plastic	67.5	59.6	72.6	45.2	97.4	68.5
Glass	2.5	0.2	1.0	0.2	0.6	0.9
Metal	17.7	9.7	21.1	8.5	33.1	18.0
Paper/cardboard	94.3	143.0	78.8	163.5	126.6	121.3
Paste	162.2	112.0	127.3	133.7	144.5	135.9

Table 10
Comparison between the obtained values of dry matter content for each waste component and those suggested by IPCC (2006)

MSW component	Dry matter content in % of wet weight	
	IPCC (2006)	Average values, new samples
Paper/cardboard	90	45
Textiles	80	47
Paste	40	47
Wood	85	64
Rubber and leather	84	82
Plastics	100	59
Metal	100	85
Glass	100	99

Table 11
MSW components expressed as dry weight percentages

Component	Percentage – dry basis (%)								
	New MSW	1 yr old	4 yr old	8.76 yr old	7.84 yr old	5.50 yr old	9.09 yr old	3.92 yr old	4.42 yr old
Stone/ceramic	10.5	16.4	13.4						
Textiles	2.6	2.0	2.5						
Rubber	0.5	0.3	0.2	59.42	50.54	59.49	52.54	57.08	66.41
Plastic	23.3	8.7	13.8						
Glass	3.5	5.2	4.1						
Metal	2.4	9.0	5.0						
Paper/ cardboard	17.1	4.2	5.2		6.05	9.74	5.52	3.65	5.60
Wood	4.0	8.1	5.7	40.58[a]	7.04	8.65	9.51	15.23	18.12
Paste	36.1	46.0	50.2		36.37	22.11	32.42	24.05	9.87
Paste VS (%)	57.9	28.7	19.8	19.68	17.97	20.95	16.19	16.04	23.21
Paste organic matter (dry basis)	20.8	13.3	9.9	7.99	6.54	4.63	5.25	3.86	2.29
Paste lignin content (%)	13	–	–	–	–	–	–	–	–

[a] Paste, wood and paper/cardboards considered together.

Table 12
Values of C_m, BF_W, $DDOC_m$ and L_o estimated using the procedures employed

Parameter	New MSW	1 yr old	4 yr old	8.76 yr old	7.84 yr old	5.50 yr old	9.09 yr old	3.92 yr old	4.42 yr old
C_m (m^3 CH_4/dry-Mg)	478.87	488.71	486.88	478	475.07	464.78	474.36	477.4	469.7
BF_W	0.263	0.150	0.120	0.060	0.090	0.090	0.080	0.070	0.070
L_o (m^3 CH_4/Mg)	65.9	38.53	31.42	14.48	22.95	22.8	20.7	18.4	17.96
$DDOC_m$	0.114	0.066	0.053	0.030	0.041	0.042	0.037	0.034	0.034
L_o (m^3 CH_4/Mg) IPCC (2006)	66.62	38.33	31.12	17.33	23.97	24.48	21.86	19.73	19.8

considered. If the IPCC (2006) method is used, an average value of L_o = 66.62 m^3 CH_4/Mg MSW is obtained (new waste). It can be noted that despite the differences in the methods used, the results presented in Table 12 are very close.

Eq. (10) was used to fit the values of L_o presented in Table 12, fixing the values of L_o = 65.9 and 66.62 m^3 CH_4/Mg MSW obtained above for each method used. Values of k = 0.21 yr^{-1} were obtained in both cases. Fig. 4 presents the obtained experimental and fitted results. The values of L_o obtained here are smaller than normally presented in the technical literature for developing tropical countries. This is probably due to the high moisture content of the waste which counterbalances the occurrence of high values of organic content (see Table 8). On the other hand, the k value obtained is compatible with environmental conditions on site (high temperature and water content), which tend to accelerate the process of organic matter depletion. There is a good agreement between the obtained values of k and the values presented in Table 5 (wet tropical climate).

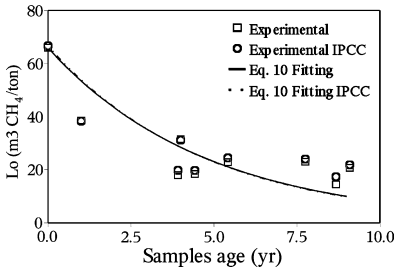

Fig. 4. Experimental $L_o(t)$ values and fitted using Eq. 10.

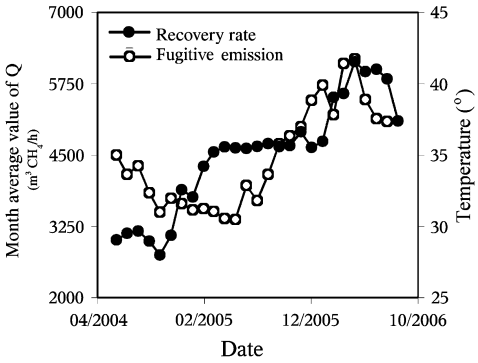

Fig. 5. Methane recovery rates and average biogas temperature.

5.2. Field results

Fig. 5 presents the average values for the rate of methane recovery and gas temperature (measured at the exit of each drain) for each month from June 2004 to August 2006. As can be seen, there is a clear dependency among the values presented. A temperature decrease was generally followed by a suction increase and vice versa (not shown in the figure). Data presented in Fig. 5 may be interpreted as resulting from non-equilibrium conditions for gas recovery (+fugitive emissions) and generation rates (ideal gas law application). The gas recovery rate is directly linked to the operational conditions of the recovery system. The number of flares and pumps used directly influences the recovery rate and it increases in a discrete way over time. On the other hand, gas generation rate is directly linked to variables such as temperature, pH, water content, etc., and it increases continuously with the increase in the mass of waste stocked. At the beginning of the process (Fig. 5), the gas recovery rate increases rapidly and the temperature decreases, indicating that the recovery plus the fugitive emissions rate gets higher than the generation rate. The recovery rate remained almost constant in the period between March 2005 and February 2006. As the generation rate increases during this period, temperature started to increase in May 2005, indicating a reversal of the initial conditions. In February 2006 the recovery system performance improved again and there was a peak in the methane extraction rate in April 2006. After that, there was an almost simultaneous decrease in the temperature and recovery rates

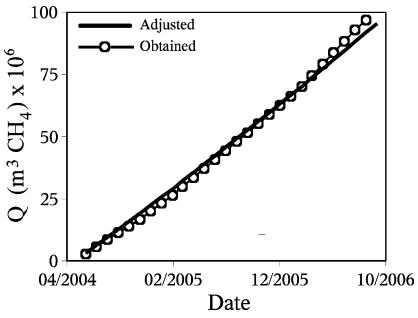

Fig. 6. Cumulative methane generation and fitted results using Eqs. 12 and 13.

(in conjunction with an increase in the values of applied gas suction), indicating that the recovery rate tends to approximate the rate of methane generation.

Fig. 6 shows the estimated landfill cumulative methane generation and the values predicted by Eqs. (12) and (13). As can be seen, there is a good adherence between the model used and the experimental results. Values of $k = 0.2\ yr^{-1}$ and $L_o = 67\ m^3\ CH_4$/Mg MSW were used in Fig. 6, which are close to those obtained from characterization data.

6. Conclusions

This paper presents some laboratory and field data obtained as part of a research program being carried out at the Metropolitan Center Landfill in Salvador, Brazil. Laboratory characterization data concerning MSW samples of varying ages have been presented and discussed, and the use of simplified procedures to estimate the methane generation potential, L_o, and the constant related to the biodegradation rate, k, have been discussed and exemplified using the obtained experimental results. The procedures adopted use waste composition and water content (as well as some data from literature concerning waste component biodegradability) to estimate the relative amount of dry organic matter that is potentially degradable.

On-site methane recovery rates are presented and analyzed and the first order decay method, developed by the USEPA (1996), is used to fit field and laboratory experimental results. It is demonstrated that despite all the assumptions and the simplicity of the adopted methods, the values L_o and k obtained in both cases are very close, making them attractive for first approach purposes.

The values of L_o obtained both on-site and in the laboratory (about $70\ m^3\ CH_4$/Mg MSW) are lower than those normally presented in the literature for developing tropical countries. This is probably due to the higher moisture content, which counterbalances high organic content. The values of k (about $0.2\ yr^{-1}$) are presumed consistent with the field conditions (high temperature and water content), which tend to accelerate the process of biodecomposition.

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