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FUGITIVE METHANE EMISSIONS FROM TWO EXPERIMENTAL BIOCOVERS CONSTRUCTED WITH TROPICAL RESIDUAL SOILS: FIELD STUDY USING A LARGE FLUX CHAMBER

Rafaela Franqueto [1], Alexandre R. Cabral [2], Marlon A. Capanema [3] and Waldir N. Schirmer [4,*]

[1] *Universidade Regional de Blumenau - FURB, Blumenau, Santa Catarina State, 89030-080, Brazil*
[2] *Université de Sherbrooke, Civil and Building Engineering, 2500, boul. de l'Université, Sherbrooke, J1K 2R1 Quebec, Canada*
[3] *Instituto Federal de Educação, Ciência e Tecnologia de Goiás, IF-GO, Goiânia, Goiás State, 74130-012, Brazil*
[4] *Universidade Estadual do Centro-oeste (UNICENTRO), Irati (Paraná State), 84500-000, Brazil*

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ABSTRACT

This study aimed at assessing the response of two experimental passive methane oxidation biocovers (PMOB) installed in a Brazilian landfill located in Guarapuava, State of Paraná. The PMOBs covered an area of 18 m² each, and were 0.70-m-thick. The first PMOB (control subarea) was constructed using the same soil used to cover closed landfill cells, i.e. a typical residual soil. The second PMOB (enriched subarea) was constructed with a mixture of the residual soil and mature compost, with a resulting organic matter content equal to 4.5%. CH_4 and CO_2 surface fluxes were measured in a relatively large (4.5 m²) static chamber. CH_4, CO_2 and O_2 concentrations were also measured at different depths (0.10, 0.20, 0.25 and 0.30 m) within PMOBs. The concentrations from the raw biogas were also measured. Methane oxidation efficiencies (Eff_{ox}) were estimated based on the CO_2/CH_4 ratio. The average CH_4 and CO_2 concentrations in the raw biogas (42% and 32%, respectively) for the 16 campaigns corroborated those typically found in Brazilian landfills. Lower CH_4 fluxes were obtained within the enriched subarea (average of 20 $g.m^{-2}.d^{-1}$), while the fluxes in the control subarea averaged 34 $g.m^{-2}.d^{-1}$. Eff_{ox} values averaged 42% for the control subarea and 80% for the enriched one. The results indicate that there is a great potential to reduce landfill gas (LFG) emissions by using passive methane oxidation biosystems composed of enriched substrates (with a higher content of organic matter).

1. INTRODUCTION

In Brazilian municipal solid waste (MSW) landfills, where there is no any biogas active recovery system in most of them, a common practice to reduce biogas emissions is to install a vertical drain – usually constructed with very coarse gravel – and flare it. These drains, which are often operated manually, are submitted to the large settlements that usually take place in landfills. Consequently, the integrity of the usually poorly maintained drains is negatively affected, reducing their capacity to drain landfill gas (LFG). In addition, Brazilian landfill covers are often constructed with readily available materials, which are placed in one single layer. Considering these premises, it can be expected that a significant proportion of the generated LFG migrates through the cover system in the form of fugitive emissions (Maciel and Jucá, 2011).

Several studies have shown that a passive biosystem (where the biogas passes through the cover naturally, without pumping it) installed in the cover system (interim or final) can be a very effective complement to active systems in reducing fugitive emissions of methane and odorous substances (Abichou et al., 2006a; Cabral et al., 2010a; Capanema et al., 2013; Capanema et al., 2014; Geck et al., 2016; Lucernoni et al., 2016; Roncato and Cabral, 2012; Sadasivam and Reddy, 2014; Scheutz et al., 2009). Most of these studies documented the performance of passive biosystems in temperate climates, while (to the authors' knowledge) no field-scale studies have been performed to document the performance of passive biosystems in Brazil (a tropical country) and employing residual soils. Such passive systems are in great need in developing countries due to the almost complete absence of active systems.

Documentation of methane, odorous substances and organic compound emissions has often relied on the use of flux chambers that cover surfaces lower than 1.0 m² (Abichou et al., 2006a,b; Gallego et al., 2014; Hudson and Ayoko, 2008; Scheutz et al., 2009; Trégourès et al., 1999). The low cost and simplicity of the static chamber

* Corresponding author:
Waldir Nagel Schirmer
email: wanasch@hotmail.com

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method resulted in its widespread use. However, given the fact that fugitive emissions are often concentrated in cracks that cover very small subareas (e.g. Geck et al., 2016; Rachor et al., 2011; Rachor et al., 2013), in addition to varying strongly in time, chances are that concentrated fluxes in these cracks will be missed during emissions assessments using small flux chambers. According to Geck et al. (2016), extrapolation of total emissions from measurements performed with small flux chambers can be questionable.

The present study documented the response of two experimental passive methane oxidation biosystems (PMOBs) installed in a Brazilian landfill where biogas is vented out passively. The landfill is located in the sub-tropical subarea of central Paraná, a southern state. The first PMOB (control) was constructed with the same residual soil that has been employed as both interim and final cover by the landfill operator. The other PMOB was constructed with this same soil after being enriched with organic-matter-rich compost. This study focused on the capacity of the two PMOBs to oxidize methane and on the magnitude of surface emissions. Oxidation efficiency was assessed by means of the CO_2 to CH_4 ratio along several gas profiles (Gebert et al., 2011a).

For this study, we designed and constructed a low-cost and easy-to-build large-scale chamber. Table 1 presents the characteristics of several flux chambers used in recently reported studies about landfill biogas emissions. Flux chambers with surfaces up to 17.7 m² and 880-L volume have been reported. Ideally, according to Rochette and Eriksen-Hamel (2008), the surface covered by the chamber and its volume should be proposed as a function of flux intensity (or biogas loading). Given the fact that the PMOBs were installed directly over the waste mass, and we did not have access to flux intensity data, our design was based on the largest possible chamber we could build and carry.

1.1 Abbreviations

AVG: Average
Eff_{ox}: Methane oxidation efficiencies
f: Biogas mass flux
FID: Flame ionization detector
GC: Gas chromatography
LFG: Landfill gas
MSW: Municipal solid waste
OM: Organic matter
PMOB: Passive methane oxidation biocover
STP: Standard temperature and pressure
TCD: Thermal conductivity detector
TOC: Total organic carbon

2. MATERIAL AND METHODS

2.1 Characterization of the study area and the cover soil

This study was carried out in a landfill located in Guarapuava, a city located in the south-central region of the State of Paraná (Brazil). This landfill has been used to dispose of non-hazardous municipal solid wastes (MSW). The authors selected a region within the landfill as flat as possible and as far away as possible from vertical drains, in order to avoid preferential pathways of the biogas to these drains, cracks on the surfaces and ensure that CH_4 was present in measurable concentrations at the surface. The cover in the selected area had been placed 4.5 years before beginning of our experiments. Chamber measurements were then performed to assess CH_4 emissions.

Within this area, two 18 m² subareas were delimited: one called the "control subarea" and the other "enriched subarea" (with compost), covered by a 0.70-m-thick residual soil layer. The spacing between each subarea was 1.0 m. The cover soil in the control subarea was the same as else-

TABLE 1: Shapes and sizes of flux chambers reported in the literature.

Shape of the chamber	Dimensions (m)		Surface (m²)	Volume (L)	Flux $g.m^{-2}.d^{-1}$	References
	Base	Height				
Rectangular	0.65	0.28	0.42	120	N.R.[1]	Chanton and Liptay (2000)
Rectangular	0.63	0.20	0.40	80	330 – 596 18.1– 117.5 Chanton et al. (2011) N.R[1]	Abichou et al. (2006b); Stern et al. (2007); Chanton et al. (2011)
Rectangular	1.80 (L) x 1.20 (W)	0.25	2.10	504	330-596 (maximum values) 18.1-117.5 (mean values) Chanton et al. (2011) N.R[1]	Capanema et al. (2013), Lakhouit et al. (2014)
Rectangular	1.22 (L) x 0.76 (W)	0.25	0.93	241	N.R.*	Capanema et al. (2014)
Quadratic	N.R.[1]	N.R.[1]	1.00	50	5.0 – 389.2	Araujo and Ritter (2016)
Quadratic	0.50 (L and W)	0.10	0.25	25	N.R.[1]	Lucernoni et al. (2016)
Quadratic	0.40 (L and W)	0.05	0.16	0.008	N.R.[1]	Monteiro et al. (2016)
Quadratic	4.2 (L and W)	0.50	17.7	880	0.98-6.69	Geck et al. (2016)
Rectangular	3.00 (L) x 1.5 (W)[2]	0.2	4.50	900		This study

[1] N.R.: not reported; [2] divided into 2 sections for ease of transportation. The sections are assembled on site.

where in the site (sandy clayey silt, 86.3% sieved through a 200-Mesh sieve); its average organic matter content is equal to 0.4%. In the enriched subarea, the uppermost 0.15 m of soil was substituted by a mixture of the mature compost (originally with 32% organic matter content) and the same natural soil, resulting in a substrate with 81.4% sieved through a 200-Mesh sieve and an organic matter content equal to 4.5%. The intention was to foster bacterial growth and assess addition of nutrients in order to improve passive methane oxidation. The pH of the soil (~6.6 for the control subarea; and 7.1 for the enriched subarea) varied very little throughout the study period. It can therefore be assumed that pH would not constitute a limiting parameter in this study. Moreover, it is known that methane-oxidizing bacteria perform better in pH near to neutrality (Delhomenie and Heitz, 2005).

The Atterberg limits determined for the control subarea were: Liquidity limit = 51%, Plasticity limit = 36%; and the Plasticity Index was 15%. The values found for the enriched subarea were: Liquidity limit = 51%, Plasticity limit = 36%; and the Plasticity Index was 16%. For the control subarea, the Standard Proctor's optimum moisture was 29.6% for a maximum dry density equal to 1.47 g/cm³, whereas the respective values for the enriched subarea were 35.6% and 1.39 g/cm³.

2.2 Characterization of raw biogas

Assessment of the characteristics of the raw biogas was performed by installing raw biogas pipes in each of the two subareas. Stainless steel pipes with a diameter of 10 mm were buried at a depth of 1.0 m in order to reach the interior of the waste mass. Once it was not possible to measure the loading rate or even the flow rate of biogas through the biocovers, the raw biogas concentration was the only parameter monitored, in order to determine the oxidation efficiency of the cover layer in both of the evaluated subareas.

The concentration of the main gases that compose the raw biogas was determined with the aid of a Columbus portable gas analyzer (Columbus Instruments Inc.) equipped with infrared sensors for detecting CO_2 and CH_4 in a range of 0-100 vol.%, and coupled to an electrochemical sensor for detecting O_2 between 0-21 vol.%. The measurement accuracy for methane and carbon dioxide is about 2% and 1% of the value read for oxygen. The biogas was sampled from the pipes using a 60-mL syringe and injected into the gas analyzer. N_2 concentrations were calculated by subtracting the sum of CO_2, CH_4 and O_2 concentrations from 100% (simplifying assumption).

2.3 Assessment of surface emissions using the large flux chamber

2.3.1 Flux chamber specifications

A flux chamber was built in a similar way to those used by Capanema et al. (2013) and Lakhouit et al. (2014); as shown in Figure 1a. It covers an area equal to 4.5 m² with a total internal volume equal to 0.9 m³.

A fishbone-shaped system with perforated copper piping was installed in the interior part of the flux chamber, in order to capture the gas from all points inside the chamber, directing them to the exit point (sampling point - Figure 1b). The frame (onto which the cover of the flux chamber rested) was inserted at 0.15 m depth and sealed with bentonite, as recommended by Capanema et al. (2014). The top of the frame had a groove where the water was poured to prevent the entry of atmospheric air during flux measurements. Each subarea had its own fixed frame.

Inside the chamber, two small battery-operated fans were installed to ensure homogenization of the emitted biogas, according to the field recommendations applied

FIGURE 1: Biogas samplings: (a) flux chamber; (b) biogas sampling point.

by Abichou et al. (2006b), Scheutz et al. (2014) and Stern et al. (2007). A mercury thermometer was also installed to measure the temperature variation inside the chamber, and thus determine the biogas concentrations according to the standard temperature and pressure (STP).

Water content probes (ECH_2O CE-5 sensor, Decagon, Pullman, USA) were installed at 0.15 m below surface in both subareas to determine the soil water content. All samples were collected respecting at least two days between the last precipitation and the sampling campaign. However, there were intense rains in the days leading up to some campaigns, considerably increasing the soil moisture content. Precipitation and atmospheric pressure data were obtained from the Weather System of Parana State database, because site-specific data was not available.

2.3.2 Sampling and analysis of CH_4 and CO_2 emissions

Sixteen campaigns were carried out to determine CH_4 and CO_2 fluxes using the chamber. Emitted biogas samples were collected at 2-minute intervals using a 60 mL syringe (Figure 1b). All samples were collected within one hour, as suggested by the UK Environment Agency (2010).

The samples were inserted into 30 mL glass vials that had been previously placed under vacuum, and then sealed with a septum "crimp" (Du et al., 2006; Jantalia et al., 2008). They were subsequently analyzed by GC-flame ionization-thermal conductivity using a Shimadzu FID-TCD, equipped with a 5-m long Carboxen 1000 packed column (60/80 mesh). The main testing parameters are as follows: oven heating ramp: 40°C (6 min); heating rate: 20°C/min up to 220°C; carrier gas: argon. Gas chromatography analysis were only required for methane concentrations below 1% (below the Columbus detection limit).

2.3.3 Surface methane mass flux calculations

Biogas mass fluxes at the surface were calculated based on the results obtained using Equation 1 (according to Cabral et al., 2010a and Perera et al., 2002), corrected for the standard temperature and pressure (STP).

$$f=(V/A)\times(\Delta C/\Delta t)\times(273{,}15/(273{,}15+T_{int}))\times(P_{atm}/1013) \quad (1)$$

where: V = internal volume of the flux chamber (m^3); A = cover layer area of the chamber (m^2); $\Delta C/\Delta t$ = represents the slope of the plot relating the change in gas concentration to time ($mg.m^{-3}.s^{-1}$); T_{int} = internal temperature of the gas in the chamber (°C); P_{atm} = atmospheric pressure (mbar).

2.4 Vertical concentration profiles of biogas

2.4.1 Installation of the gas probes

Five nests of stainless steel gas probes were placed in each subarea, as shown in Figure 2. In each nest, the 10-mm (internal diameter) gas probes were inserted using a metal auger to desired position (0.10, 0.20, 0.25 and 0.30 m) below the surface, following the methodology described by Cabral et al. (2010a). After insertion, the upper ends were capped with a rubber septum.

2.4.2 Determining gas concentrations

Concomitantly with the 16 flux measurements, campaigns were also performed for determining the gas concentrations along the cover layer of the two evaluated subareas. First, each gas probe was purged of the volume of air initially contained therein using a 60 mL syringe. After one hour, a biogas sample was collected and analyzed in the portable gas analyzer "Columbus". Again, gas chromatography analysis were only required for methane concentrations below the Columbus detection limit (≅1%).

2.5 Estimation of methane oxidation efficiency (Eff_{ox}) based on gas profile data

The share of oxidized methane (x) at a certain depth was determined in both subareas, according to Equation 2 (Gebert et al., 2011b).

$$(CO_{2_{LFG}}+x)/(CH_{4_{LFG}}-x)=CO_{2\_i}/CH_{4\_i} \quad (2)$$

where x = share of oxidized CH_4 (vol.%), CH_{4-LFG} = CH_4 concentration of the landfill gas (vol.%), CO_{2-LFG} = CO_2 concentration of the landfill gas (vol.%), CH_{4-i} = CH_4 concentration at depth i (vol.%), CO_{2-i} = CO_2 concentration at depth "i" (vol.%).

The ratio between the percentage of oxidized methane at the depth of 0.10 m and the methane concentration in the raw biogas (CH_4_LFG) determines the methane oxidation efficiency (Eff_{ox}) in % according to Equation (3) (Gebert et al., 2011b). One important hypothesis associated with this method relates to soil respiration. The amount of CO_2 produced by soil respiration needs to be negligible compared to the CO_2 produced due to methane oxidation (Geck et al., 2016). It is assumed herein that respiration is negligible. We base this assumption on results presented by Gebert et al. (2011b), who found, in a batch experiment using soil with total organic carbon (TOC) 4.9%-7.5%, that

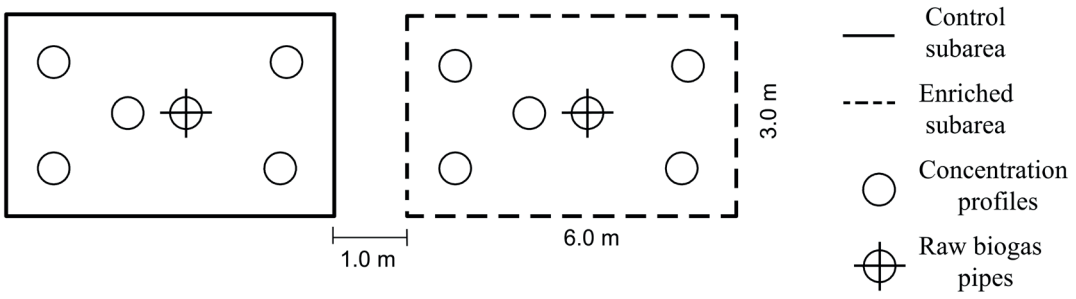

FIGURE 2: Concentration profiles of the subareas (enriched and control).

CO_2 respiration accounted for less than 2% of the observed CO_2 production. In the same study, the oxidation efficiency was only slightly overestimated when a soil with 6% organic matter was tested.

$$Eff_{ox} = (x/CH_{4_{LFG}})\ x\ 100 \quad (3)$$

where x = share of oxidized CH_4 (vol.%), CH_{4-LFG} = methane concentration in the landfill gas (vol.%).

3. RESULTS AND DISCUSSION

3.1 Raw biogas characterization

The concentration values of CH_4, CO_2 and O_2 in the raw biogas are shown in Figure 3. Raw biogas samples were collected at a depth of 1.0 m below the surface. The average (AVG) CH_4 concentration in the raw biogas for the 16 campaigns was 42% (with standard deviation, σ equal to ±4.49%). For CO_2, the AVG concentration was 32% (σ=±2.53). The concentration ranges in Figure 3 are typical of Brazilian landfills (Audibert and Fernandes, 2013; Candiani et al., 2011). The presence of O_2 in the waste is not a surprise. Despite near optimal conditions for accelerated waste degradation, cover systems in most landfills in Brazil (and in the developing world) are often composed of a single layer of soil; cracks can be formed during dry periods, thereby allowing penetration of atmospheric air. In fact, O_2 penetration has been documented for landfills in several subareas of the globe, including the UK (Barry et al., 2003), Iceland (Kjeld et al., 2014), Australia (Obersky et al., 2018) and Brazil (Audibert and Fernandes, 2013).

3.2 Evaluation of the surface emissions

Surface methane mass flux and soil temperatures (at 0.10 m depth) throughout the 16 campaigns and in each subarea are shown in Figure 4.

Methane fluxes in the control subarea ranged between 0 and 53 $g.m^{-2}.d^{-1}$ (AVG=34 $g.m^{-2}.d^{-1}$ and σ=±13.5), whereas methane fluxes in the enriched subarea varied between 0 and 49 $g.m^{-2}.d^{-1}$ (AVG=20 $g.m^{-2}.d^{-1}$ and σ=±15.3). On Feb 22nd, the soil was too wet and there was no noticeable

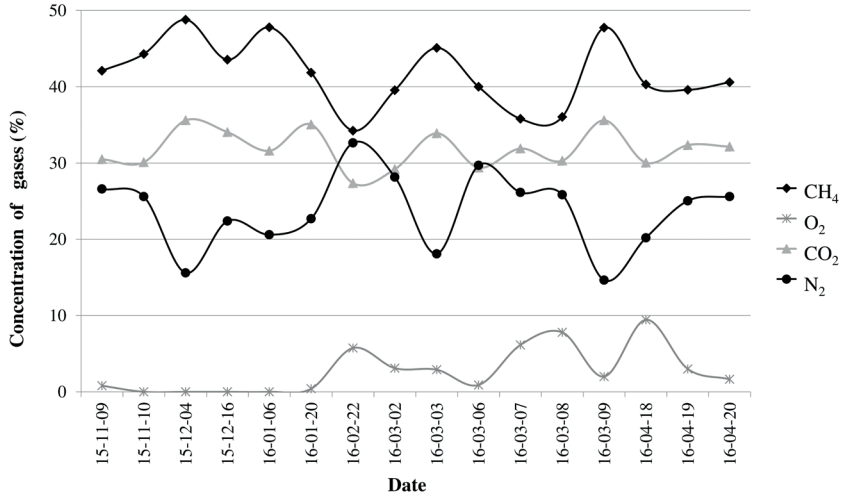

FIGURE 3: Average concentration of raw biogas throughout the 16 campaigns.

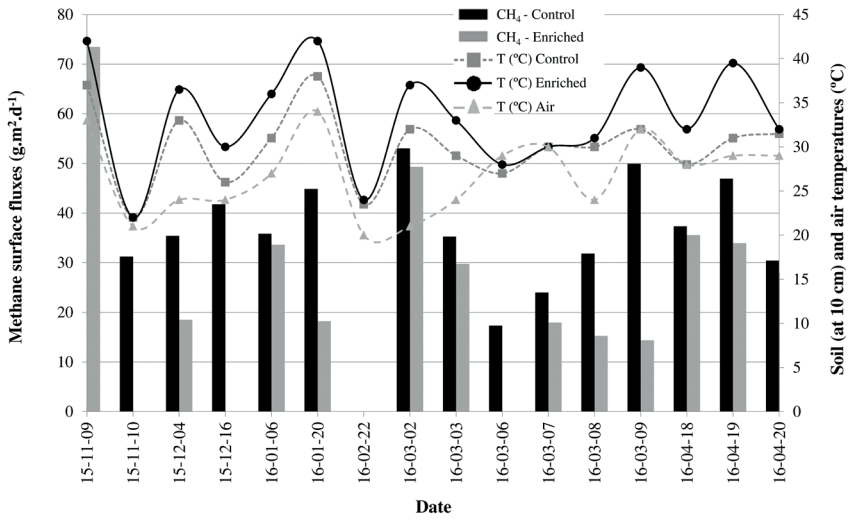

FIGURE 4: Surface methane mass fluxes ($g.m^{-2}.d^{-1}$), air and soil temperatures for both subareas.

increase in gas concentrations inside the flux chamber over several hours. Consequently, fluxes were considered equal to zero in both zones for this particular date. It is noteworthy that CH_4 fluxes in the enriched subarea were always lower or much lower than in the control subarea, with the exception of the first field campaign (on Nov. 9th, 2015) in the enriched subarea, when the microorganisms were probably acclimatizing and adapting to the environment.

Abichou et al. (2009) also compared an organic-rich biocover with an organic-poor cover and observed much lower CH_4 fluxes from the organic-rich biocover. The slightly lower average methane flux on the surface of the compost-enriched subarea may be associated with the greater organic matter content, which created better conditions for the development of ubiquitous methanotrophic bacteria (Humer and Lechner, 2001). An in-depth study using modern microbiology analysis tools could not be performed to confirm the preceding assertion.

The air temperature varied between 20 and 33°C during the 16 campaigns, while inside the interim cover soils temperatures varied between 22 and 38°C (control) and between 22 and 42°C (enriched), respectively. The higher soil temperatures within the enriched subarea (Figure 4) probably resulted from more intense microbial activity. Carbon dioxide mass fluxes are shown in Figure 5.

In the control subarea, CO_2 fluxes vary between 33 and 721 $g.m^{-2}.d^{-1}$ (AVG=251 $g.m^{-2}.d^{-1}$; σ=±168), while in the enriched subarea they vary between 0 and 794 $g.m^{-2}.d^{-1}$ (AVG=316 $g.m^{-2}.d^{-1}$; σ=±245). Fernandes (2009) reported CO_2 fluxes in Brazilians landfills between 0 and 388 $g.m^{-2}.d^{-1}$, and between 29 and 233 $g.m^{-2}.d^{-1}$ for conventional and enriched (soils), respectively.

The carbon dioxide surface flux is higher than the methane flux in the enriched area for most of the assays (e.g. data from January 20th and March 9th, 2016 in Figure 4 and Figure 5), highlighting the higher conversion of methane to carbon dioxide and water. A similar trend was reported by Christophersen et al. (2001), who found carbon dioxide emissions of 90 $g.m^{-2}.d^{-1}$, slightly higher than those found for methane (75 $g.m^{-2}.d^{-1}$). Scheutz et al. (2011) verified this increase in carbon dioxide emission in lysimeters with mature and stable compost.

Despite CH_4 emissions being considered equal to zero on Feb. 22nd, 2016, due to wet conditions, CO_2 concentration increases were measurable in the two zones for this same date. It can only be speculated that minimal soil respiration near the surface led to these non-zero values.

3.3 Vertical profiles of biogas

An average of the biogas composition for all set of gas probes along vertical profiles in the first 30 cm of the cover layer for both control (Figure 6a) and enriched (Figure 6b) subareas are presented.

The fact that the CH_4 and CO_2 curves cross at different depths (0.13 m for control subarea – Figure 6a - and 0.23 m for enriched subarea – Figure 6b) indicates a previous methane oxidation in the enriched subarea and, therefore, a highest capacity of oxidation of this substrate.

Figure 6 also shows that oxygen was present throughout the profile. The average percentage of oxygen remained between 12.4% (control subarea) and 13.9% (enriched subarea). According to Czepiel et al. (1996); Gebert et al. (2003); Jugnia et al. (2008), an oxygen concentration >3% is sufficient for the oxidation reaction. Therefore, oxygen was never a limiting parameter for methanotrophic activity. In addition, it can be observed that O_2 concentrations decreased in the profile due to soil retention and microbial methane oxidation.

The degrees of saturation were calculated using volumetric data of water content. The degree of saturation is between 71% (control area) and 80% (enriched area). According to Huber-Humer and Lechner (2003), the ideal degree of saturation for methanotrophic activity is between 40 and 80%. The degrees of saturation always remained lower than 85%, which approximately corresponds to the

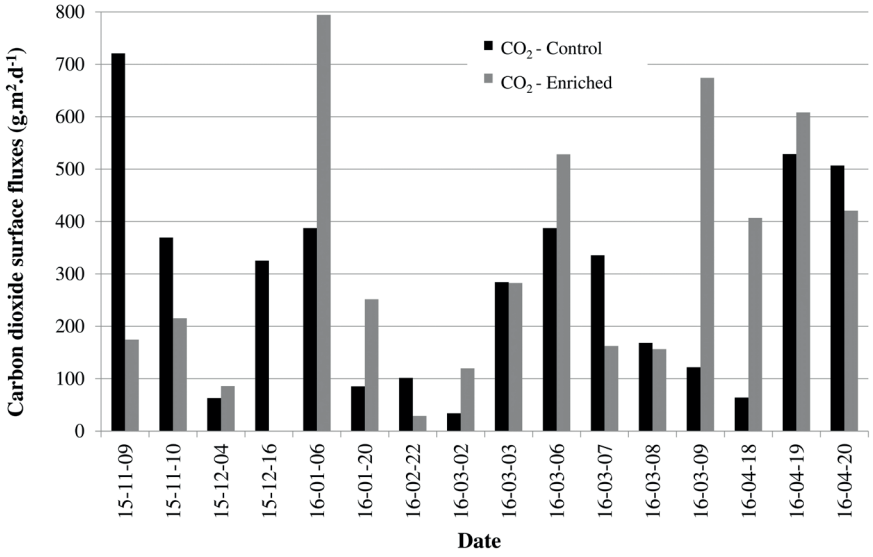

FIGURE 5: Surface carbon dioxide mass fluxes ($g.m^{-2}.d^{-1}$) for both subareas.

degree of saturation value beyond which air becomes occluded in the pores of fine grained soils (Nagaraj et al., 2006), such as the one used to construct the experimental covers. Consequently, with the exception of the near-zero CH_4 flow observed on Feb 22nd, no impedance to flow was observed. It is also worth pointing out that when soil moisture content increases (as observed on Feb 22nd), the upward flow of CH_4 and the downward flow of O_2 in the oxidation layer become limited to diffusion in the liquid phase, delaying the oxidation process (Cabral et al., 2010b).

3.4 Methane oxidation efficiencies

Figure 7 presents the average oxidation efficiencies of methane (Eff_{ox}) for the control and enriched subareas, calculated by Equation (3).

Figure 7 shows that the methane oxidation capacity varied over time and was affected by the type of material constituting the cover soil. Indeed, the methane oxidation efficiencies of the enriched subarea were always higher than in the control subarea. The mean efficiencies of methane oxidation at 0.10 m were 42% (±1.56%) and 80% (±1.88%) for the control and enriched subareas, respectively. The average CH_4 surface emissions were 34 and 20 $g.m^{-2}.d^{-1}$, respectively.

These results corroborate findings by several other studies. For example, Abichou et al. (2009) reported maximum methane efficiency equal to 63% for the control subarea in a landfill in Florida, while in the biocover it was 100%. Rose et al. (2012) obtained a maximum CH_4 oxidation efficiency of 67% for a conventional cover layer, while improving it with compost led to a maximum of 97%. Capanema et al. (2013) found a methane oxidation efficiency of 95.8% in a biocover whose O.M. content was similar to the top soil in the enriched subarea reported in the present study. Einola et al. (2008) observed that 96% of the methane was oxidized near the surface, where the topsoil was richer in organic matter.

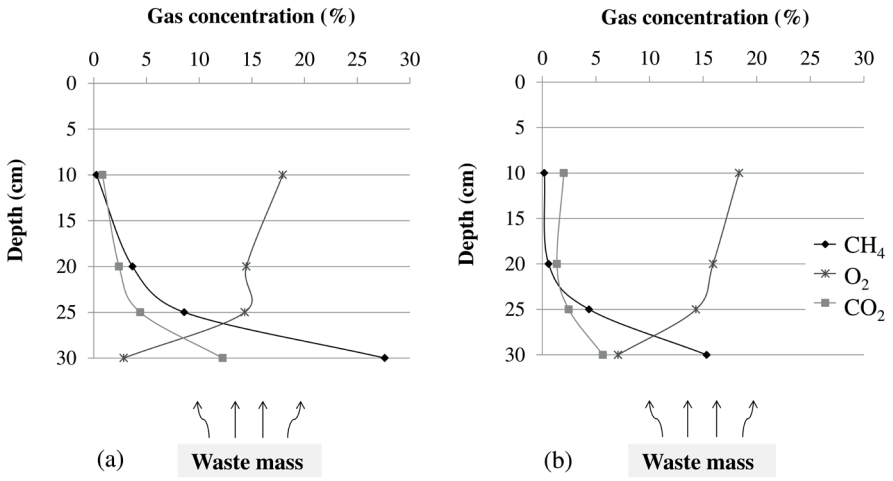

FIGURE 6: Vertical composition profiles of biogas for control (a) and enriched (b) subareas.

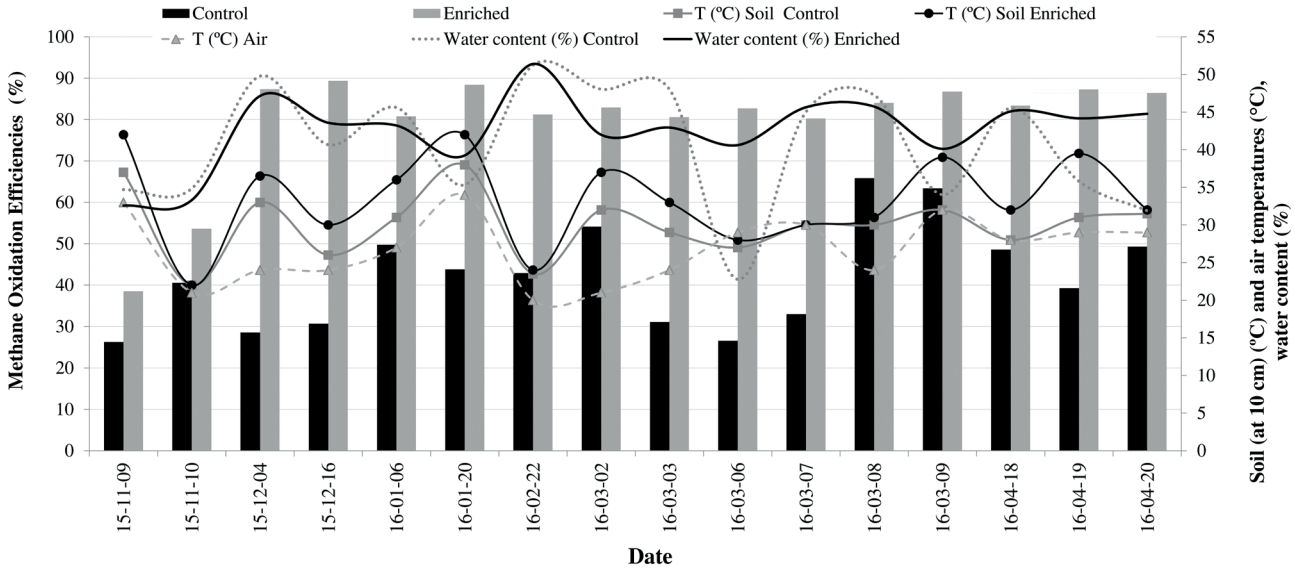

FIGURE 7: Methane oxidation efficiencies (Eff_{ox}) in the control and enriched subareas.

4. CONCLUSIONS

This study reported the capacity of two experimental passive methane oxidation biosystems (PMOBs) consisting of tropical soils typically found in developing nations. One of them was supplemented with organic-rich material (enriched subarea). In general, the average CH_4 and CO_2 concentrations in the raw biogas (42% and 32%, respectively) for the 16 campaigns corroborated those typically found in Brazilian landfills. The presence of oxygen in raw biogas resulted from atmospheric air penetration in the thin, single-layer cover, mainly through cracks.

The methane oxidation capacity was quite high for both subareas (control and enriched). Oxidation efficiencies (at a depth of 0.10 m) averaged 42% for the control subarea and 80% for the enriched area. CH_4 and CO_2 surface fluxes averaged 20 $g.m^{-2}.d^{-1}$ and 316 $g.m^{-2}.d^{-1}$ in the organic-matter-enriched subarea during the monitoring period, while those measured in the control subarea averaged 34 $g.m^{-2}.d^{-1}$ and 251 $g.m^{-2}.d^{-1}$, respectively. It is noteworthy that the surface fluxes were obtained using a custom-made 4.5-m² flux chamber, which allows for better representativeness of surface fluxes, because it allows inclusion of cracks and other imperfections that may affect measurements.

The lower CH_4 fluxes and higher oxidation efficiency in the enriched subarea can be associated with the greater organic matter content in the enriched subarea, which created more favourable conditions for the development of ubiquitous methanotrophic colonies (Humer and Lechner, 2001). Temperature conditions, which ranged from 20 to 42°C at the surface and within the first 10 cm of the cover, favoured methane oxidation.

The results obtained in this study point to the great potential in reducing residual LFG emissions by landfills located in developing nations using low-cost PMOBs constructed with typical tropical soils.

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