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Scientific Paper

Application of linear and non-linear methods in estimating fugitive emissions by using flux chamber at the Jockey Club Controlled Landfill in Brasília/DF

Aplicação dos métodos linear e não linear na estimativa de emissões fugitivas utilizando placa de fluxo no Aterro Controlado do Jockey Club em Brasília/DF

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ABSTRACT

The Landfill Gas (LFG) generated in municipal solid waste (MSW) landfills consists of the main greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2). Cover layer systems of sanitary landfills are designed to mitigate the LFG emission into the atmosphere and control water infiltration. Thus, this research aims to quantify and evaluate CH_4 and CO_2 accurate emissions in the final cover layer system at the Jockey Club Controlled Landfill in Brasília (ACJC) by using the static flux chamber. The emission results were estimated by adjusting the concentration data obtained in 12 tests in the cover layer by the methods of Linear Regression (LR) and the Non-Steady-State Diffusion Flux Estimator (NDFE). Fugitive emissions ranged from 0 to 685.6 g CH_4 m^{-2} day^{-1} and 0 to 1,563.94 g CO_2 m^{-2} day^{-1} using the LR method. Using the NDFE method, emissions up to 4.2 and 2.5 times greater than the LR method were estimated for CH_4 and CO_2, respectively.

Keywords: Gas transport; Methane oxidation; Sanitary landfill; Static flux chamber; Cover layer.

RESUMO

O biogás gerado em aterros de resíduos sólidos urbanos (RSU) é constituído pelos principais gases do efeito estufa, como metano (CH_4) e dióxido de carbono (CO_2). As camadas de cobertura de aterros sanitários são executadas para mitigar a emissão do biogás para a atmosfera e controlar a infiltração de água. Assim, esta pesquisa visou quantificar e avaliar as emissões pontuais de CH_4 e CO_2 na camada de cobertura definitiva no antigo Aterro Controlado Jóquei Clube de Brasília (ACJC), utilizando a placa de fluxo estática. Os resultados de emissão foram estimados ajustando os dados de concentração obtidos em 12 ensaios na cobertura pelos métodos da regressão linear (RL) e o *non steady state diffusion flux estimator* (NDFE). As emissões fugitivas variaram de 0 a 685,6 gCH_4 m^{-2} dia^{-1} e de 0 a 1563,94 gCO_2 m^{-2} dia^{-1} utilizando-se o método RL. Por meio do método NDFE, estimaram-se emissões até 4,2 e 2,5 vezes maiores do que pelo o método RL para CH_4 e CO_2, respectivamente.

Palavras-chave: Transporte de gás; Oxidação de metano; Aterro sanitário; Placa de fluxo estática; Camada de cobertura.

INTRODUCTION

Municipal solid waste (MSW) is extremely relevant in current socio-environmental discussions due to its increasing generation and the development of logistics to manage it. Hence, there is increasing concern over the presence of toxic substances in soil and groundwater as a result of industrial activities and their associated methods since they can affect both biotas, soil, and water (VIEIRA *et al.*, 2023).

Among the systems that make up a landfill, the definitive cover layer is necessary to isolate the waste from the external environment after its closure, performing the function of protecting human health and the environment (SANTOS, 2009). The main objectives of the cover layer are to reduce rainwater infiltration, limit the uncontrolled release of gases from the landfill into the atmosphere, eliminate the proliferation of diseases, provide an adequate surface for revegetation of the site, and eliminate the exhalation of odors (TCHOBANOGLOUS; FRANK, 2002).

In Brazil, most landfills are covered by a homogeneous layer of compacted clayey soil (conventional layer) under vegetation that avoids problems with soil erosion and shrinking (LOPES *et al.*, 2010). Most landfills use a conventional layer system, typically consisting of layers of compacted clay liner (CCL), geomembranes, geosynthetic clay liner (GCL), or a combination of these materials

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(MARIANO, 2008). The choice of the most appropriate material depends on the characteristics of the waste, the operation of the landfill, and the cost of materials available in the region (LEMOS *et al.*, 2023).

Regattieri (2009) states that the thickness of the soil used as cover influences the gas transport time, and that the thicker the layer, the slower the gas percolation by diffusion, and the greater the possibility of the gas being retained in soil pores, with physical, chemical or biological retention potentially occurring.

Due to the great importance attributed to the landfill cover layer, it is common to use techniques to quantify fugitive emissions, such as the use of static flux chamber. The method consists of a closed chamber embedded in the covering soil, and is designed to capture the gas that escapes from the cover layer into the atmosphere, and then the variations in gas concentration are recorded over time to determine the emission flux of a small and specific area (corresponding to the size of the chamber) of the cover layer (DEED *et al.*, 2004; MARSHALL; BROWELL; SMITH, 2010). Extensive research suggests that the flux chamber is the most used, simple and economical technique for quantifying surface trace gas emissions, having been used for more than 30 years mainly for greenhouse gases (HÜPPI *et al.*, 2018).

Emission estimates using the static flux chamber test are commonly calculated using different mathematical methods. The most used is the Linear Regression — LR method (VENTEREA, 2013). However, in a static flux chamber test, the gas concentration theoretically follows a non-linear profile due to the variation in diffusion rates (HÜPPI *et al.*, 2018). Thus, Livingston, Hutchinson and Spartalian (2006) developed the Non-Steady-State Diffusion Model (NDFE), which is one of the only gas emission models that is time-dependent, derived from diffusion theory and applicable to concentration data from a chamber in a non-steady state.

The importance of knowing fugitive emissions from the cover layer of a landfill contributes to monitoring the efficiency of gas capture systems, the cover system, and to subsidizing remediation projects for the harmful effects of emissions. Fugitive methane emission rates reported in the literature range from -0.29 to 14,794 g m^{-2} day^{-1}, and can represent up to 22% of total landfill gas emissions (MACIEL, 2009). The wide variation shows the dependence of the flux on a set of internal and external waste factors, on the particularities of each landfill and the region in which it is located (MACIEL, 2009).

In this context, projects for the use and energy harnessing of methane have been stimulated in the context of Clean Development Mechanisms (CDM), in view of the reduction of uncontrolled emissions of this gas into the atmosphere, generating electrical energy from alternative sources. However, LFG recovery projects in Brazil are limited to large-scale projects and recovery projects for dumps and controlled landfills (LOPES *et al.*, 2010).

The Jockey Club Controlled Landfill in Brasília – *Aterro Controlado do Jockey Club* (ACJC), also known as the old *Lixão da Estrutural* (Estrutural Dump), where the Waste Receiving Unit (URE) currently operates, is one of several cases of an originally inadequate and unplanned disposal site in Brazil. The old ACJC has had an open-air storage configuration for many years, which is why it does not have bottom waterproofing, causing serious problems for the environment and the health of the population that have already been recorded historically. In particular, the main impacts are on the Brasília National Park and on the satellite city of Vila Estrutural, with a vulnerable population, experiencing groundwater contamination and strong smells due to gas leaks (FREITAS, 2020).

Therefore, this research aims to evaluate specific GHG emissions released by the ACJC in the final cover layer to contribute to studies that complement the development of technologies in the URE. Emission estimates were carried out using a static flux chamber at 12 points in the ACJC cover layer. As a research and comparison criterion, emissions were estimated using the LR and NDFE methods, and the application of each method was discussed.

METHODOLOGY

The purpose of this study was to determine the emission of CH_4 and CO_2 in the final cover layer of the Jockey Club Controlled Landfill in Brasília (ACJC). To achieve this, field experiments were conducted using a static flux chamber. In 2018, the Environmental and Energetic Remediation Project for the Jockey Club Controlled Landfill (RAEESA) was initiated, and the results of this research supported the project.

Study area

The study area is the current Waste Receiving Unit — *Unidade de Recebimento de Entulho* (URE), previously known as *Lixão da Estrutural* (Estrutural Dump), which became the Jockey Club Controlled Landfill (ACJC) when it kept improper disposal activities going on according to the National Solid Waste Policy — *Política Nacional de Resíduos Sólidos* (PNRS). The unit is located in the Federal District (DF) near the capital of Brazil, Brasília.

The URE became a waste receiving point after the closure of inappropriate activities in the ACJC. The final cover layer of the old ACJC consists of a combination of clayey soil and Construction and Demolition Waste (CDW). The disposition of CDW as cover was not planned; it was arranged according to the logistics of internal truck circulation routes (FREITAS, 2020). Hence there is no record of the locations and periods when the waste was disposed of. There is also no data and information in the literature and local reports regarding the thickness of the final cover layer of the old ACJC.

The sampled area is located in the portion corresponding to the intermediate landfill, the main waste disposal area. The spacing between tests was planned in order to get a greater distribution of points in the area, increasing the representativeness of emissions in relation to the total landfill area.

Measurements of methane (CH_4) and carbon dioxide (CO_2) concentration were taken in field in the old ACJC from August 1st, 2019, to November 29th, 2019. In total, 12 surface measurements were taken in an area of approximately 700 m^2. Figure 1 shows the locations of the sampled surface points, the delimitation of the area where measurements were taken, and burners near the tests.

Field analyses

The device used for gas measurement was the GEM 5000. The device was specifically designed to monitor gas extraction systems in landfills through sensors that analyze the concentration of gases CH_4, CO_2, O_2 (in % volume), and CO and H_2S (in ppm), which may form LFG.

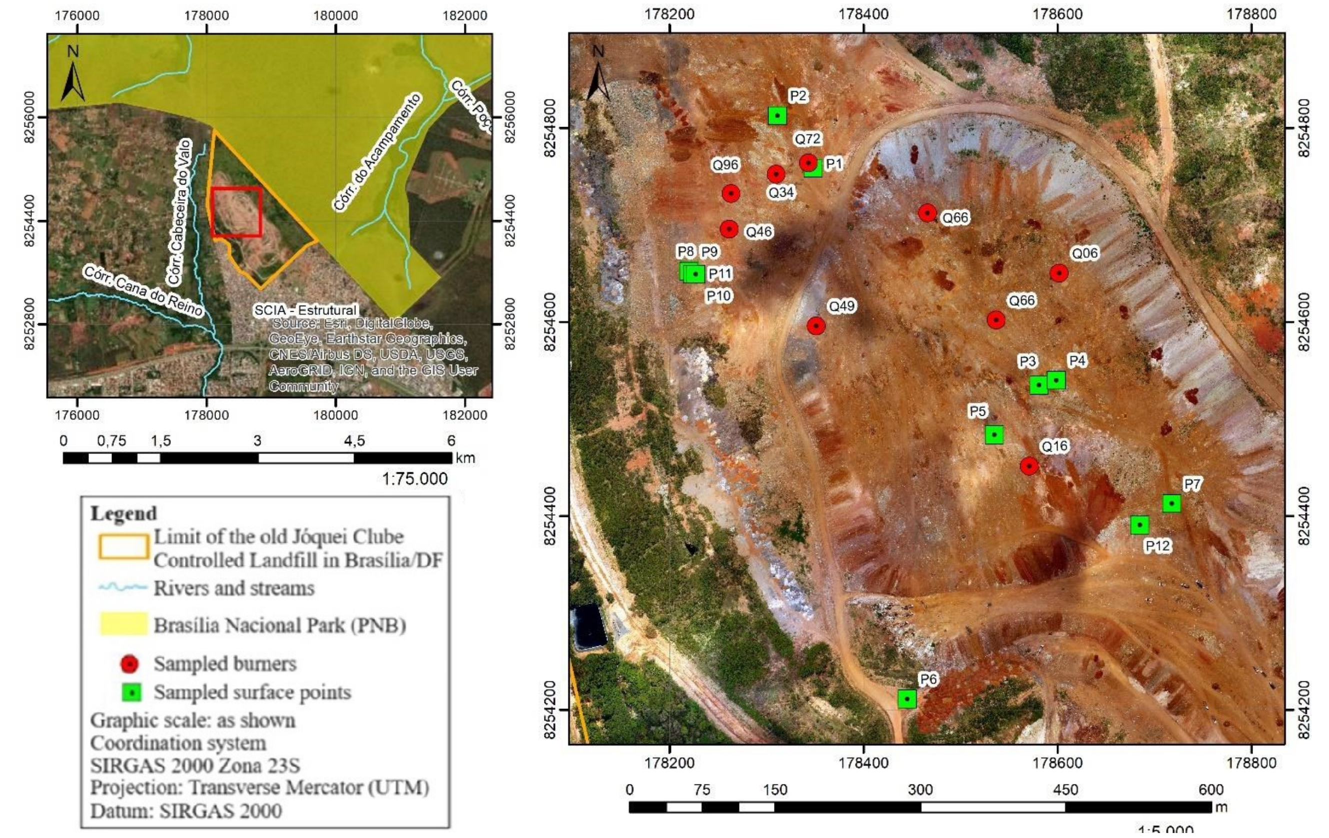
The methodology used to quantify accurate emissions of CH_4 and CO_2 in the cover layer was that of the static flux chamber. The dimensions, material, and testing methodology were supported by the Guidance for Monitoring Landfill Gas Surface Emissions (MARSHALL; BROWELL; SMITH, 2010), in the researches developed by Maciel (2003, 2009), and Mariano and Jucá (2010).

The first stage of the test consists of the prototype project and the flux chamber (Figure 2), a rectangular box with an open base and in the shape of a step, made of galvanized steel with dimensions of 0.62 × 0.56 × 0.117 m, with a usable area of 0.345 m^2 and a volume of 0.0345 m^3. There are two outlet connections (quick connect type) at the top of the chamber, used to connect the gas analyzer through polyethylene tubes.

The stepped shape aims to prevent horizontal air entry, as suggested by Mariano e Jucá (2010). Thus, the usable volume filled with LFG is the total volume of the chamber, and the cross-sectional area for LFG passage is that of the chamber's larger base. Furthermore, the sealing of the lateral ends of the chamber in the chamber-soil contact was determined using the local moist soil.

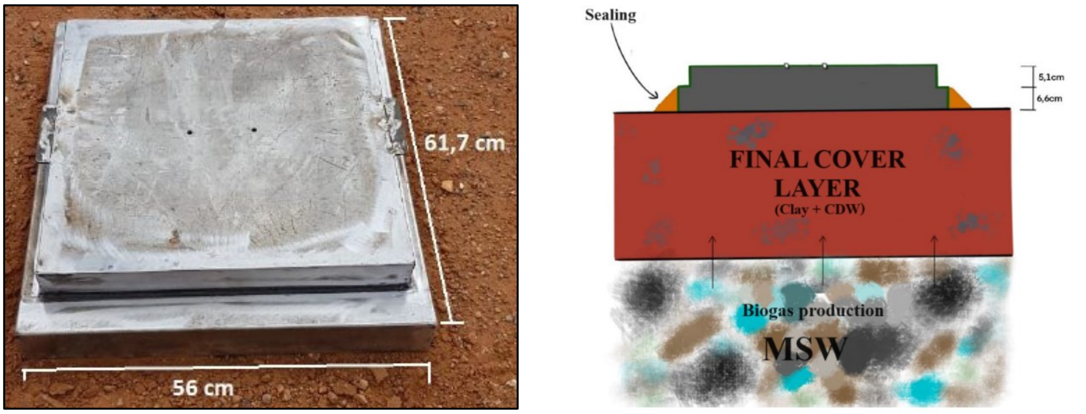
The test locations (Figure 3) were based on field identification of possible emission hotspots, such as cracks, soil erosion, or bubbling liquids present on the surface.

The quantification of emissions at the sampling point is carried out by recording the gas concentration resulting from the flux chamber test according



Source: Farias (2020).

Figure 1 – Measurement points in the final cover layer of the Jockey Club Controlled Landfill in Brasília.



Source: Farias (2020).

Figure 2 – Static flux chamber for measurements in the cover layer.

to the following procedures: i. the chamber is placed at the designated location and marks its perimeter (0.62 × 0.56 m); ii. its sides are sealed with clay moistened with water to prevent horizontal gas flow inside the chamber; iii. the gas suction and return tubes are connected to the chamber's output connectors and then to the GEM5000 device to initiate the reading procedure. The sequence of steps is necessary to prevent the accumulation of gases inside the chamber before starting the concentration measurements.

Flux estimation

Gas flux estimation was conducted using both linear (Linear Regression — LR) and non-linear (Non-Steady-State Diffusion Flux Estimator — NDFE) models. The choice to calculate using both methods was due to criticisms regarding the accuracy of flux values obtained through the linear model and the proposal developed by Livingston, Hutchinson and Spartalian (2006) for being more realistic and effective in calculating flux for testing data using a flux chamber.

Both methods use a fitted equation obtained by regression applied to concentration data acquired from the static flux chamber test. However, for model application, it is necessary to use concentration values (obtained in %/Δt) in terms of density (ML^{-3}). Mass concentration is obtained through Equation 1 by multiplying the concentration (in %) by the density of the analyzed gas (ML^{-3}), which must be adjusted to the internal chamber temperature.

$$J = \frac{V_{PLATE}}{A_{PLATE}} \cdot \rho_i \cdot \frac{\Delta C}{\Delta t} \tag{1}$$

Where: J is the measured gas flux [$ML^{-2}T^{-1}$], $V_{chamber}$ is the volume of the chamber [L^3], $A_{chamber}$ is the usable area of the chamber [L^2], ρ_i is the gas density at a given temperature [ML^{-3}], $\Delta C/\Delta t$ is the change in gas concentration over time (% vol./[T]).

Assuming mass continuity principles, the NDFE method is an exact solution to a partial differential equation (PDE) that describes the transport of gases from the soil, at depth $z = 0$ (soil-atmosphere interface) to the static flux chamber derived by Livingston, Hutchinson and Spartalian (2006) and given by Equation 2:

$$C_t = C_0 + f_0 \tau \left(\frac{A}{V}\right)\left[\frac{2}{\sqrt{\pi}}\sqrt{\frac{t}{\tau}} + \exp\left(\frac{t}{\tau}\right)\operatorname{erfc}\left(\sqrt{\frac{t}{\tau}}\right) - 1\right] \tag{2}$$

Where: C_t is the gas concentration in the chamber at time t of the test; C_0 is the initial gas concentration; f_0 is the flux density at the surface ($z = 0$) at the time of installing the flux chamber

[$MT^{-1}L^{-2}$] and τ is a time constant [T]. τ represents the time in which the concentration gradient will tend to disappear in response to the increase in concentration inside the chamber. C_0, f_0 and τ are model adjustment parameters. Furthermore, according to Livingston, Hutchinson and Spartalian (2006):

$$\tau = \left(\frac{V}{A}\right)^2 \left(\theta_a D_p\right)^{-1} \tag{3}$$

Where: θ_a is the volumetric moisture content of the air [L^3L^{-3}] and D_p is the gas diffusion coefficient in the soil [L^2T^{-1}]. When τ is small, the soil concentration gradient, and therefore the diffusive transport of gas into the chamber, will decrease more quickly than when τ is large.

RESULTS AND DISCUSSION

Cover layer

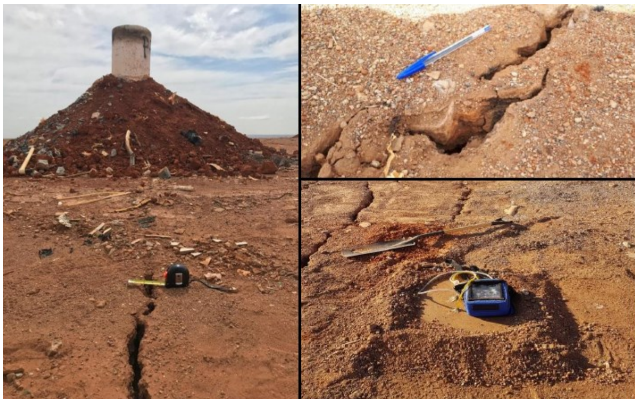
The final cover layer in which the measurements were taken is predominantly composed of clayey soil mixed with fragments of ceramic blocks, wood, plastics, pipes, bricks, hoses and pieces of construction materials that form a mixed aggregate of granular compounds.

Although there are no monitoring records, a high degree of compaction of the covering layer material was observed. From inspection trenches excavated at the site, it was observed that the cover layer is in the order of 3 m thick.

Flux chamber testing

The concentration results of methane (CH_4) and carbon dioxide (CO_2) gases over time obtained in each test are shown in Figures 4 and 5, respectively. Table 1 presents a summary of the field results in each surface measurement in the cover layer. In addition, LFG concentrations were measured in burners near the tested points, and the LFG composition varied from 46.1 to 55.9% for CH_4, and from 33.9 to 47.9% for CO_2. Since it presents higher CH_4 values, it can be stated that the biodegradation of waste landfilled in this part is in the methanogenic phase.

In general, 5 out of the 22 curves (Figures 4 and 5) obtained in the cover layer tests indicated gas flow into the atmosphere. Thus, points P1 and P2 indicated emission



Source: Farias (2020).

Figure 3 – Locations with a crack.

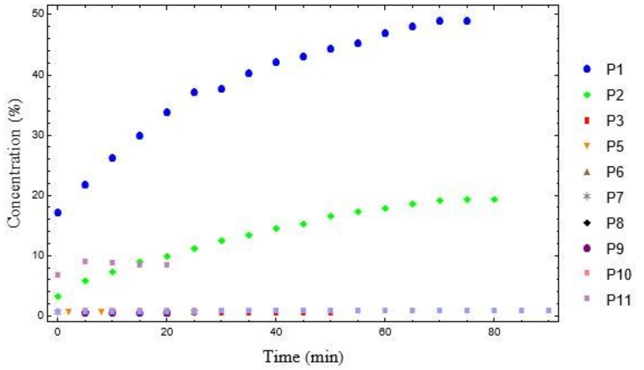


Figure 4 – CH_4 concentration at sampling points.

of CH_4, and points P1, P2 and P12 showed emission of CO_2, since in these locations there was an increase in the concentration of gases followed by stabilization. P4 was not shown in Figures 4 and 5 for having insignificant concentration values.

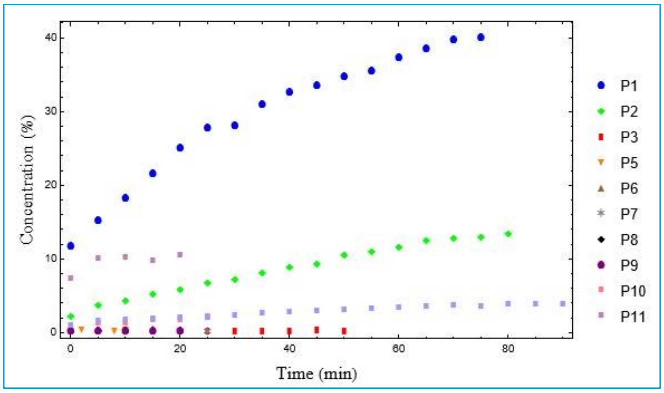


Figure 5 – CO_2 concentration at sampling points.

As seen in Figure 4, at point P1 the CH_4 concentration varied from 17 to 49%, and the CO_2 concentration started at 11.4% and stabilized at 39.8%. In P2 this variation was from 3.2 to 19.4% for CH_4, and from 2 to 13.1% for CO_2. As for points P3, P4, P5, P6, P7, P8, P9, P10, P11 and P12, the tests showed a behavior in which the concentrations were low (less than 1%) and not increasing. The exception is P11, where, despite having an initial concentration of 6.5 and 7% of CH_4 and CO_2 respectively, the subsequent concentrations showed stability and decreased.

For all the tests analyzed, the O_2 concentration values also varied little and presented figures close to its concentration in the atmosphere, as shown by the records of 20.6 and 20.7% at the end of the tests at points P3, P5 and P12 (Table 1).

In Table 1, the points that showed an increasing behavior in the concentration of gases in the chamber were P1 and P2. Point P12 only had an increase in concentration for CO_2, being the only gas analyzed for that point. Thus, the points at which the linear (LR) and non-linear (NDFE) methods were applied were P1, P2 and P12.

The application of LR to the analyzed samples is shown in Figures 6, 7 and 8. The LR method had a good application to data from tests P1, P2 and P12,

Table 1 – Static flux chamber test data at the Jockey Club Controlled Landfill in Brasília.

Point	Test Date (dd/mm/yyyy)	CH_4 concentration (%)	CO_2 concentration (%)	O_2 concentration (%)	Temperature (°C)
P1	05/08/2019	49	39.8	5	27
P2	01/08/2019	19.4	13.1	-	28
P3	05/08/2019	0.6	0.2	20.6	28
P4	05/08/2019	-	-	-	28
P5	05/08/2019	0.5	0.2	20.7	28
P6	14/08/2019	0.3	0.3	-	28
P7	14/08/2019	0.3	0	-	28
P8	14/08/2019	0.4	0.1	-	28
P9	14/08/2019	0.4	0.1	-	28
P10	14/08/2019	0.5	1.7	-	28
P11	14/08/2019	8.1	10.2		28
P12	08/11/2019	0.5	3.7	15.3	30

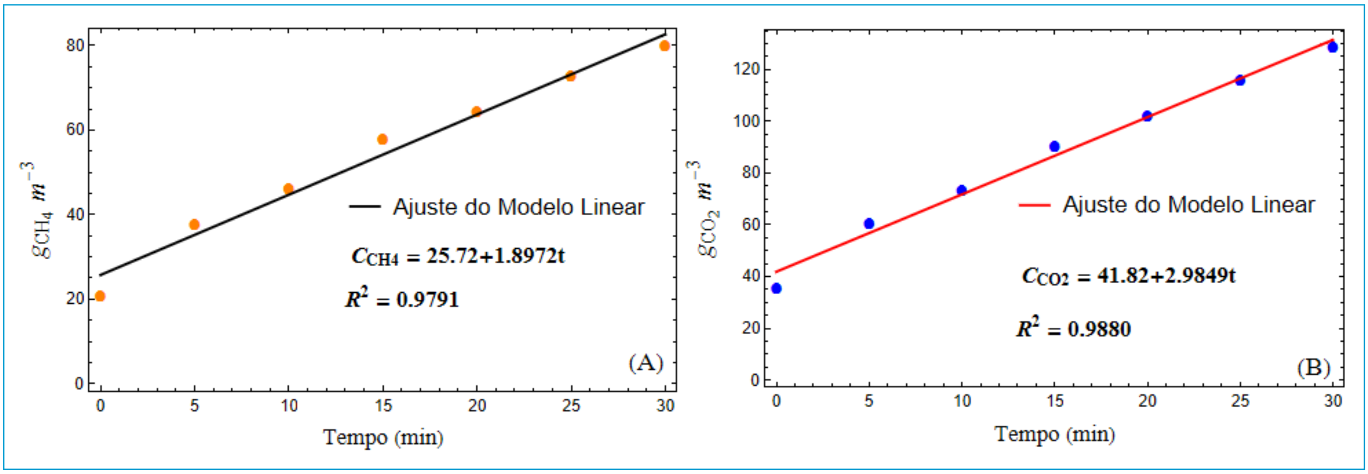


Figure 6 – Linear Regression adjustment at point P1 for gases (A) CH_4 and (B) CO_2.

with a coefficient of determination (R^2) greater than 96%. Figures 9, 10 and 11 show the adjustments obtained by applying the NDFE model (LIVINGSTON; HUTCHINSON; SPARTALIAN, 2006) to the CH_4 and CO_2 concentration data in the tests (P1, P2 and P12). For point P12, only the CO_2 emission was adjusted since CH_4 was not measured to allow adjustment of the methods.

Overall, the NDFE model was applied to the data with excellent determination, with all R^2 being greater than 97%. The proximity between model and experimental data increases the reliability of the method due to its accuracy to the concentration data measured with the static flux chamber. The adjustment parameters shown in Figures 9 to 11 for each test are given in minutes (τ), g m^{-3} (C_0) and g m^{-2} min^{-1} (f_0). The C_0 results were consistent with the gas concentration at the time of implementation of the chamber. The f_0 values are the flux values considered when installing the chamber for each gas. The time constant (τ) results present higher values for tests with lower emissions, thus, for P12 (Figure 11) there was a high value due to the very low emission value at that point. However, for point P2 (Figure 10) there were low values due to high emission numbers.

Furthermore, the value of the effective diffusion coefficient of gas in the soil ($\theta_a \times D_p$) was calculated using Equation 3. Table 2 shows the calculated value for each point and each gas. As a comparison criterion, the molecular diffusion coefficient for CH_4 and CO_2 in the air is in the order of 2.16×10^{-5} m²s^{-1} and 1.66×10^{-5} m²s^{-1}, respectively (FENG *et al.*, 2020). For both gases (CH_4 and CO_2), we can conclude from Table 2 that there was a high value of $\theta_a x D_p$ in P1, which may be related to the crack in the cover layer at the analyzed point, thus, there may also be advective transport due to its dimensions. For P2, there were

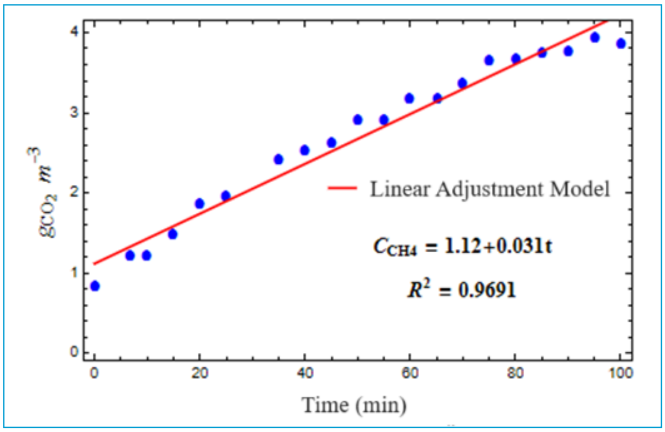


Figure 8 – Linear Regression adjustment at point P12 for gas CO_2.

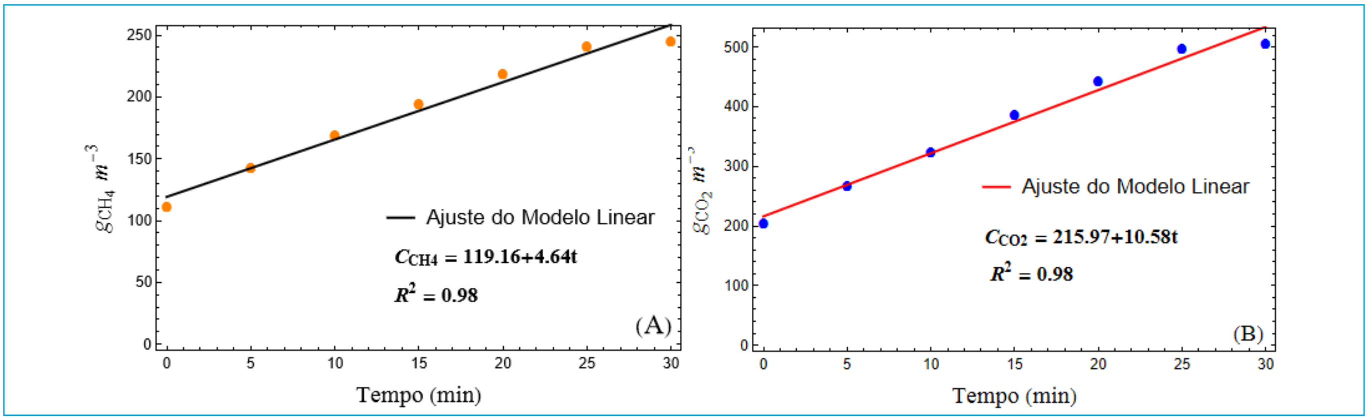


Figure 7 – Linear Regression adjustment at point P2 for gases (A) CH_4 and (B) CO_2.

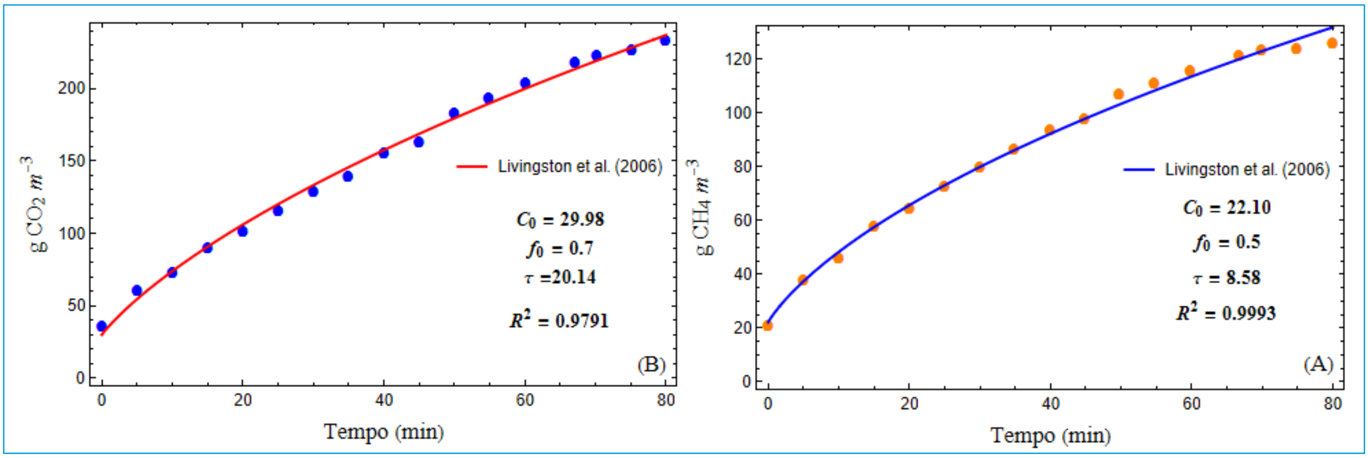


Figure 9 – Non-Steady-State Diffusion Flux Estimator adjustment at point P1 for gases (A) CH_4 and (B) CO_2.

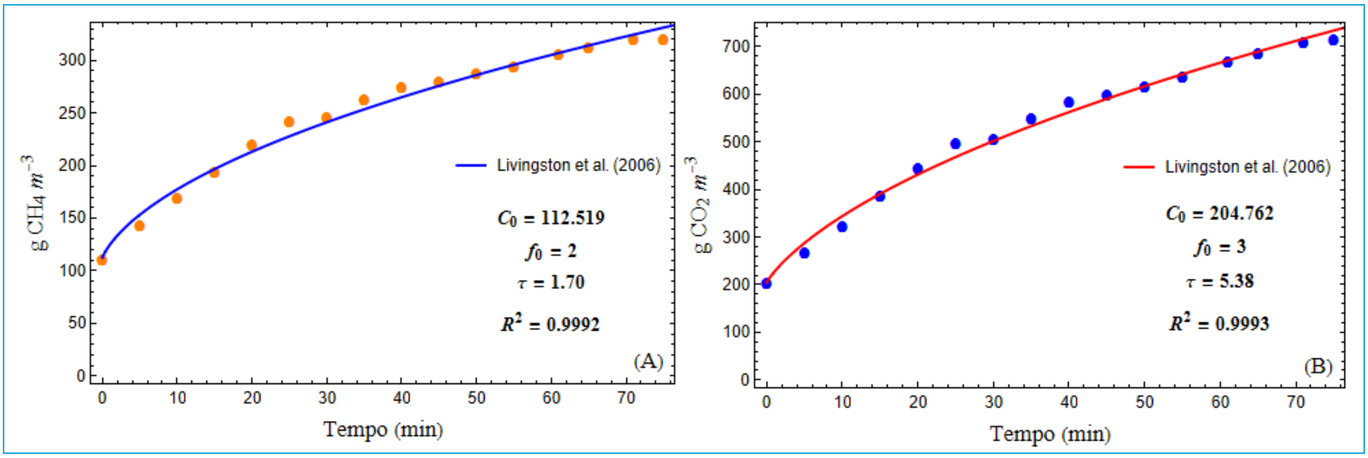


Figure 10 – Non-Steady-State Diffusion Flux Estimator adjustment for point P2 and gases (A) CH_4 and (B) CO_2.

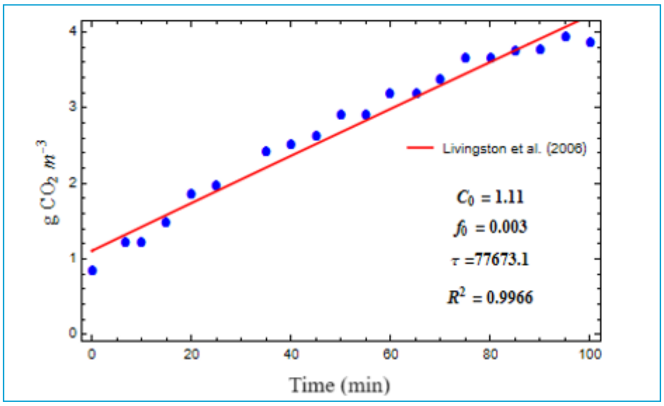


Figure 11 – Non-Steady-State Diffusion Flux Estimator adjustment for point P12 of CO_2.

Table 2 – Effective molecular diffusion for CH_4 and CO_2 at testing points.

Point	$\theta_a\ D_{CH4}$ (m² s^{-1})	$\theta_a\ D_{CO2}$ (m² s^{-1})
P1	1.02×10^{-4}	3.26×10^{-5}
P2	2.05×10^{-5}	8.71×10^{-6}
P12	-	2.26×10^{-9}

values of $\theta_a x D_p$ close to the diffusion value in air for both gases (CH_4 and CO_2). The point was also evaluated in a crack and in fact the entire emission process appears to be through diffusive transport. However, as the value of the diffusion coefficient is in the order of the diffusion value of CH_4 and CO_2 in the air, the crack shows the inefficiency of the cover layer material in this point. For P12, a low molecular diffusion value was calculated, showing the low emission in this point and the efficiency of the cover layer.

Table 3 presents the emission values for CH_4 and CO_2 using the LR and NDFE models. Eight of the tests carried out in the cover layer were not shown because GHG emissions were not measured using the static flux chamber. Considering the Linear Regression (LR) method, the CH_4 fluxes in measurements taken in the cover layer varied from 0 to 685.6 g m^{-2} day^{-1} and for CO_2 from 4.59 to 1,563.94 g m^{-2} day^{-1}. In test P12, CO_2 emissions were only verified with a total of 4.71 g m^{-2} day^{-1}. Although the emission of CH_4 is lower, it is more harmful to the environment since it retains more heat; therefore, the study of this gas is more careful in cover layers of landfills.

Considering the NDFE model (Table 3), it was estimated that P1 emits 2,879.21 g CH_4 m^{-2} day^{-1}, while point P2 emits 720 g CH_4 m^{-2} day^{-1}. Even though they are within the range of fugitive emissions found in the literature, these are high values and do not come close to any of the emissions found in landfills in Brazil. Nevertheless, it is crucial to note that all findings reported in the literature regarding landfill emissions in Brazil have utilized the LR method for estimating fugitive emissions. Furthermore, regardless of the methodology used, the high measurements are attributed to the presence of cracks in the cover layer.

For the measurements in the cover layer that showed CH_4 emission (points P1 and P2), the transient flux profiles obtained by the NDFE method are presented together in Figure 12. From the result, it is observed that the CH_4 flux at the beginning of the test is maximum and decreases with time. Thus, when the chamber is installed, there is a maximum concentration gradient and, as the volume of gas increases in the chamber space, the gradient decreases until the gas occupies the entire chamber, decreasing and tending to zero flux.

As the initial moment of the test is theoretically the closest representation to reality of the concentration gradient and flux existing on the landfill cover without the presence of the chamber, it is inferred that the initial flux is the closest to the real flux emitted by that point. Therefore, the values presented in Table 3 refer to time $t = 0$ in the NDFE model, representing the theoretical value at the beginning of the flux chamber installation.

CONCLUSION

From the results obtained, it can be concluded that the static flux chamber test for accurate measurements of GHG emissions through the definitive covering layer of the old ACJC proved to be a simple and easy-to-apply methodology. However, the execution methodology becomes complex for applying it in soils with granular characteristics. Nevertheless, sealing it with humidified clay was sufficient to obtain good accurate measurement results.

Using the static flux chamber, it was found that significant GHG emissions are escaping through the cover layer system at the ACJC, primarily due

Table 3 – Greenhouse gas flux by Linear Regression and Non-Steady-State Diffusion Flux Estimator methods.

Point	LR		NDFE	
	CH_4 flux (g m^{-2} day^{-1})	CO_2 flux (g m^{-2} day^{-1})	CH_4 flux (g m^{-2} day^{-1})	CO_2 flux (g m^{-2} day^{-1})
P1	685.60	1,563.94	2,879.21	4,320.00
P2	280.33	441.05	720.00	1,008.00
P12	0.00	4.59	0.00	4.71

LR: Linear Regression; NFDE: Non-Steady-State Diffusion Flux Estimator.

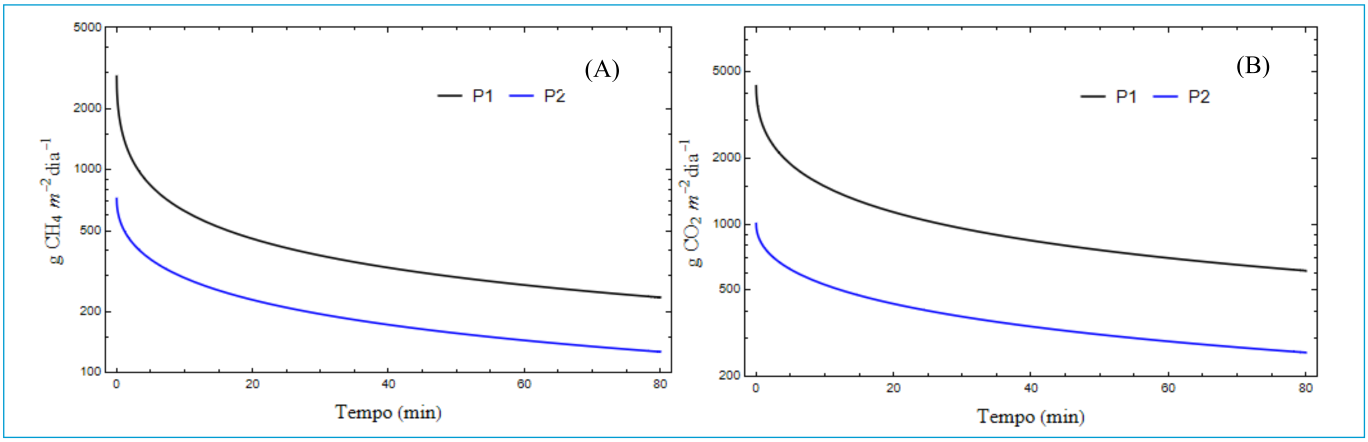


Figure 12 – Transient flux by the Non-Steady-State Diffusion Flux Estimator model for gases (A) CH_4 and (B) CO_2.

to the cracks. Thus, CH_4 emissions of up to 685.6 g m^{-2} day^{-1} were measured at the points analyzed in the cover layer; therefore, there is a potential for energy generation and revenue being wasted in the ACJC.

The fugitive emission values varied widely with tests taken in the cover layer. The final methane flux result varied from 0 to 685.6 g m^{-2} day^{-1}. Thus, out of the ten points analyzed, there were CH_4 and CO_2 emissions in two points, and there was CO_2 emission measured in one. In addition to fugitive emissions, LFG composition measurements in the burners were measured (46.1 to 55.9% CH_4, and 33.9 to 47.9% CO_2) concluding that biodegradation in the sampled area is in the methanogenic phase.

Given that only two out of the ten analyzed points exhibited significant greenhouse gas (GHG) emissions, and that the elevated emissions are correlated with the presence of cracks of notable thickness, it can be affirmed that, in terms of fugitive emissions, using construction and demolition waste (CDW) is effective as a landfill cover layer. The lack of data regarding the configuration of this soil cover composed of CDW did not allow evaluating the factors that are retaining the fugitive emission of LFG. However, it was observed that the high degree of compaction of this material and the large thickness of the layer analyzed (estimated to be around 3 m) are factors that influence the efficiency of the covering material and the reduction in CH_4 and CO_2 emissions.

Most studies estimating fugitive emissions in Brazil typically use the static flux chamber and then adjust the results based on linear regression (LR). But this study suggests that a non-linear adjustment approach (NDFE) may provide more accurate insights. The fluxes obtained using NDFE were four times higher than those found using LR, indicating that NDFE leads to higher emission estimates. Thus, a more thorough and careful analysis of the results obtained through LR is necessary. Future studies should incorporate other measurement methods alongside the static flux chamber to determine which adjustment method (linear or NDFE) is most appropriate for this specific application.

Furthermore, the measurements in the cover layer exemplify that *hotspots* such as cracks are important points with high emissions and solutions to minimize emissions and must be implemented. The surface tests P1 and P2 were carried out close to a burner (Q72), and for this study showed that regions close to drains are more prone to the appearance of cracks.

AUTHORS' CONTRIBUTIONS

Lemos, M.A.C.: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. Freitas, T.P.: Conceptualization, Investigation, Methodology, Validation, Visualization. Costa, M.A.: Conceptualization, Methodology, Visualization, Writing – Review & Editing. Cavalcante, A.L.B.: Funding Acquisition, Project Administration, Resources, Software, Supervision.

REFERENCES

DEED, C.; BOURN, M.; BRAITHWAITE, P.; DUCKWORTH, G.; GRONOW, J.; MALEHAM, M.; ROOKSBY, J.; ROSEVEAR, A.; SMITH, R. Guidance on the management of landfill gas. Bristol: Environment Agency, 2004.

FENG, S.-J.; ZHU, Z.-W.; CHEN, Z.-L.; CHEN, H.-X. Analytical model for multicomponent landfill gas migration through four-layer landfill biocover with capillary barrier. International Journal of Geomechanics, v. 20, n. 3, p. 04020001, 2020. https://doi:10.1061/(asce)gm.1943-5622.0001598

FREITAS, T.P. Avaliação de emissões de gases do efeito estufa pelo Aterro Controlado do Jockey Clubde Brasília/DF. 2020. 102 f. Trabalho de Conclusão de Curso (Curso de Engenharia Ambiental) – Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, 2020.

HÜPPI, R.; FELBER, R.; KRAUSS, M.; SIX, J.; LEIFELD, J.; FUß, R. Restricting the nonlinearity parameter in soil greenhouse gas flux calculation for more reliable flux estimates. PLoS ONE, v. 13, n. 7, p. e0200876. 2018. https://doi.org/10.1371/journal.pone.0200876

LEMOS, M.A.C.; BARAN, C.T.; CAVALCANTE, A.L.B.; PALMEIRA, E.M. A semi-analytical model of contaminant transport in barrier systems with arbitrary numbers of layers. Sustainability, v. 15, n. 23, p. 16299, 2023. https://doi.org/10.3390/su152316299

LIVINGSTON, G.; HUTCHINSON, G.; SPARTALIAN, K. Trace gas emission in chambers - A non397 steady-state diffusion model. Soil Science Society of America Journal, v. 70, n. 5, p. 1459-1469, 2006. https://doi.org/10.2136/sssaj2005.0322

LOPES, R.L.; JUCÁ; J.F.T.; MARIANO, M.O.H.; MACIEL, F.J. Camadas de cobertura metanotróficas como alternativas para gerenciamento de gases de efeito estufa em aterros sanitários. Holos, v. 4, p. 3-18, 2010. https://doi.org/10.15628/holos.2010.461

MACIEL, F.J. Estudo da geração, percolação e emissão de gases no aterro de resíduos sólidos da Muribeca/PE. 2003. 173 f. Dissertação (Mestrado em Engenharia Civil), Programa de Pós-Graduação em Engenharia Civil, Universidade Federal de Pernambuco, Recife, 2003.

MACIEL, F.J. Geração de biogás e energia em aterro experimental de resíduos sólidos urbanos. 2009. 333 f. Tese (Doutorado em Engenharia Civil), Programa de Pós-Graduação em Engenharia Civil, Universidade Federal de Pernambuco, Recife, 2009.

MARIANO, M.O.H. Avaliação da retenção de gases em camadas de cobertura de aterros de resíduos sólidos. 2008. 243 f. Tese (Doutorado em Engenharia Civil) – Programa de Pós-Graduação em Engenharia Civil, Universidade de Pernambuco, Recife, 2008.

MARIANO, M.O.H.; JUCÁ, J.F.T. Ensaios de campo para determinação de emissões de biogás em camadas de cobertura de aterros de resíduos sólidos. Engenharia Sanitária e Ambiental, v. 15, n. 3, p. 223-228, 2010. https://doi.org/10.1590/S1413-41522010000300004

MARSHALL, R.; BROWELL, D.; SMITH, S. Guidance for monitoring landfill gas engine emissions. Bristol: Environment Agency, 2010.

REGATTIERI, C.R. Quantificação da emissão de biogás em aterro sanitário - estudo de caso do aterro sanitário de São Carlos. 2009. 138 f. Tese (Doutorado em Engenharia Civil). Escola de Engenharia de São Carlos, Universidade de São Paulo, p. 137, 2009.

SANTOS, T.F.L. Estudo experimental da camada de cobertura do Aterro Morro do Céu, Niterói – RJ. 2009. 145 f. Dissertação (Mestrado em Engenharia Civil) – Programa de Pós-Graduação em Engenharia Ambiental, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2009.

TCHOBANOGLOUS, G.; FRANK, K. *Handbook of solid waste management*. 2. ed. New York: McGraw-Hill, 2002.

VENTEREA, T. Theoretical comparison of advanced methods for calculating nitrous oxide fluxes using non-steady state chambers. *Soil Science Society of America Journal*, v. 77, n. 3, p. 709-720, 2013. https://doi.org/10.2136/sssaj2013.01.0010

VIEIRA, G.M.D.; LEMOS, M.A.C.; CAVALCANTE, A.L.B.; CASAGRANDE, M.D.T. Effectiveness of polyvinylidene fluoride fibers (PVDF) in the diffusion and adsorption processes of atrazine in a sandy soil. *Sustainability*, v. 15, n. 5, p. 11729, 2023. https://doi.org/10.3390/su151511729