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PERFORMANCE OF LANDFILL COVER LAYERS IN REDUCING GREENHOUSE GAS (GHG) EMISSIONS: AN ASSESSMENT THROUGH LABORATORY TESTS

DESEMPENHO DAS CAMADAS DE COBERTURA DE ATERROS DE RESÍDUOS SÓLIDOS NA REDUÇÃO DE EMISSÕES DE GASES DE EFEITO ESTUFA (GEE): AVALIAÇÃO POR MEIO DE ENSAIOS DE LABORATÓRIO

DESEMPEÑO DE LAS CAPAS DE COBERTURA DE RELLENOS SANITARIOS EN LA REDUCCIÓN DE EMISIONES DE GASES DE EFECTO INVERNADERO (GEI): EVALUACIÓN MEDIANTE ENSAYOS DE LABORATORIO

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ABSTRACT

Objective: To assess, under laboratory conditions, the performance of sandy-clay soil and composted-substrate cover layers exposed to methane flow and simulated wetting. Theoretical framework: The analysis integrates geotechnical and physicochemical properties, gas transport, and the application of materials in landfill covers. Method: The materials were characterized and two PVC columns, one per material, were monitored with 65 cm of filling and an upward CH_4 flow of 4 NL/h. Monitoring included four sampling drains and moisture, temperature, and electrical-conductivity sensors; after approximately 40 days, simulated wetting was applied and a further monitoring stage was conducted. Results and discussion: Measured profiles showed CH_4 attenuation along the columns and distinct responses between materials and test stages. Before wetting, reported mean apparent removal was 93% for soil and 88.4% for substrate; after wetting, reported estimates were 22.42% and 99.33%, respectively. Since outlet readings are close to or below the detector quantification limit (1% v/v), these percentages are interpreted as apparent estimates and are not attributed exclusively to biological oxidation. Research implications: The results provide a comparative experimental basis for geotechnical-environmental assessment of cover materials and highlight the combined influence of material structure and water regime. Originality/value:

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The study compares local soil and composted substrate under a common protocol, tracking gases and environmental variables in two laboratory configurations.

Keywords: Solid Waste Landfills. Cover Layers. Methane. Greenhouse Gases. Environmental Geotechnics.

RESUMO
Objetivo: Avaliar, em laboratório, o desempenho de camadas de solo areno-argiloso e substrato compostado submetidas à passagem de metano e a umedecimento simulado. Referencial teórico: A análise articula propriedades geotécnicas e físico-químicas, transporte gasoso e aplicação de materiais em coberturas de aterros. Método: Foram caracterizados os materiais e monitoradas duas colunas de PVC, uma por material, com 65 cm de preenchimento e fluxo ascendente de CH_4 de 4 NL/h. O acompanhamento incluiu quatro drenos de amostragem e sensores de umidade, temperatura e condutividade elétrica; após cerca de 40 dias, realizou-se umedecimento simulado e nova etapa de leituras. Resultados e discussão: Os perfis medidos mostraram atenuação de CH_4 ao longo das colunas e respostas distintas entre materiais e etapas. Antes do umedecimento, foram reportadas remoções aparentes médias de 93% para o solo e 88,4% para o substrato; após o evento, as estimativas reportadas foram 22,42% e 99,33%, respectivamente. Como as leituras de saída se aproximam ou ficam abaixo do limite de quantificação do detector (1% v/v), os percentuais são interpretados como estimativas aparentes, sem atribuição exclusiva à oxidação biológica. Implicações da pesquisa: Os resultados oferecem base experimental comparativa para a avaliação geotécnico-ambiental de materiais de cobertura e destacam a influência conjunta da estrutura do material e do regime hídrico. Originalidade/valor: O estudo compara um solo local e um substrato compostado sob protocolo comum, acompanhando gases e variáveis ambientais em duas configurações laboratoriais.

Palavras-chave: Aterros de Resíduos Sólidos. Camadas de Cobertura. Metano. Gases de Efeito Estufa. Geotecnia Ambiental.

RESUMEN
Objetivo: Evaluar en laboratorio el desempeño de capas de suelo areno-arcilloso y sustrato compostado sometidas al flujo de metano y a humectación simulada. Marco teórico: El análisis integra propiedades geotécnicas y fisicoquímicas, transporte de gases y aplicación de materiales en coberturas de rellenos sanitarios. Método: Se caracterizaron los materiales y se monitorearon dos columnas de PVC, una por material, con 65 cm de relleno y flujo ascendente de CH_4 de 4 NL/h. El seguimiento incluyó cuatro drenes de muestreo y sensores de humedad, temperatura y conductividad eléctrica; después de aproximadamente 40 días se aplicó humectación simulada y se realizó otra etapa de medición. Resultados y discusión: Los perfiles medidos mostraron atenuación de CH_4 a lo largo de las columnas y respuestas distintas entre materiales y etapas. Antes de la humectación, se informaron remociones aparentes medias de 93% para el suelo y 88,4% para el sustrato; después, las estimaciones informadas fueron 22,42% y 99,33%, respectivamente. Como las lecturas de salida están próximas o por debajo del límite de cuantificación del detector (1% v/v), los porcentajes se interpretan como estimaciones aparentes, sin atribución exclusiva a la oxidación biológica. Implicaciones: Los resultados ofrecen una base experimental comparativa para evaluar materiales de cobertura desde la geotecnia ambiental y destacan la influencia conjunta de la estructura del material y del régimen hídrico. Originalidad/valor: El estudio compara un suelo

local y un sustrato compostado bajo un protocolo común, con seguimiento de gases y variables ambientales en dos configuraciones de laboratorio.
Palabras clave: Rellenos Sanitarios de Residuos Sólidos. Capas de Cobertura. Metano. Gases de Efecto Invernadero. Geotecnia Ambiental.

1 INTRODUCTION

The disposal of municipal solid waste in landfills generates biogas, the migration of which through the cover layers can contribute to greenhouse gas emissions. From an environmental geotechnical perspective, these layers must balance hydraulic and geomechanical behavior with the control of gas transport. Bio-covers also exploit oxygen diffusion and conditions favorable to the microbial oxidation of CH_4; their performance depends on the material properties and the hydrological regime (Chiemchaisri *et al.*, 2012; Sadasivam & Reddy, 2014). The disposal of municipal solid waste in landfills produces biogas under predominantly anaerobic conditions. For Brazil, the study estimates that 81.6 million metric tons of MSW will be generated in 2024 and indicates that 59.7% of the volume sent for final disposal was directed to sanitary landfills (ABREMA, 2025). Since some methane can escape through the cover, the surface layer plays a dual role: limiting water infiltration and reducing fugitive emissions. Biocovers aim to combine gas transport, oxygen availability, and conditions for microbial oxidation of CH_4; their effectiveness, however, depends on the material's properties and the hydrological regime (Chiemchaisri *et al.*, 2012; Sadasivam & Reddy, 2014).

Conventional mineral covers can retain or divert gases, but a reduction in concentration along a column does not, in and of itself, equate to the biological conversion of methane. The distinction is crucial: physical retention, dilution, flow restriction, and oxidation are distinct processes that require adequate evidence to be distinguished from one another. The literature links oxidation to properties such as porosity, oxygen diffusion, moisture, temperature, pH, and nutrient availability (Gebert *et al.*, 2011; Frasi *et al.*, 2020; Niemczyk *et al.*, 2021). Composted materials can provide a porous structure and nutritional support, but their performance and stability depend on their composition and maturity. Studies on bio-coverings document both oxidation potential and sensitivity to operational conditions, justifying comparative trials on a controlled scale before extrapolating to the field (Abichou *et al.*, 2020; Bajwa *et al.*, 2022; Scheutz *et al.*, 2022). This study evaluates the laboratory performance of sandy-clay soil layers and composted substrate, based on tests conducted by Soares (2026). The focus is on describing CH_4 attenuation, O_2 profiles, and the response of environmental variables to gas flow and simulated wetting, thereby contributing comparative evidence to environmental geotechnics without extrapolating beyond the scope of the tests.

2 THEORETICAL FRAMEWORK

2.1 LANDFILL COVERS AND MITIGATION MEASURES

In bio-covers, methane from the waste mass passes through a distribution layer and a biologically active layer, where it can encounter oxygen and methanotrophic microorganisms. The flux and oxidation result from the balance between the diffusion of CH_4 and O_2, water content, and porous structure; high saturation can restrict the gas phase, while excessive drying can inhibit microbial activity (Gebert *et al.*, 2011; Frasi *et al.*, 2020).

2.2 MATERIAL PROPERTIES AND RESPONSE TO MOISTURE

Organic compounds have been studied for their ability to support biological activity and, in some cases, increase oxidation potential; nitrogen availability is also discussed as a factor that can influence methanotrophic activity (Bajwa *et al.*, 2022; Niemczyk *et al.*, 2021; Tong *et al.*, 2025). Nevertheless, geotechnical and chemical characterization does not replace direct measurement of methane transformation, and performance observed in the laboratory should not be taken as field efficiency. Column experiments allow for the comparison of profiles and controlled conditions, but their interpretation depends on instrumentation, replicates, and the distinction between retention and conversion (Kightley *et al.*, 1995; Liu *et al.*, 2024).

2.3 GAS TRANSPORT AND INTERPRETATION OF ATTENUATION

The purpose of this subtopic is to explain how the pore structure and physical properties of the medium influence the migration of CH_4 and O_2, and how these processes should guide the interpretation of column experiments. In cover layers, methane rises from the waste mass, while oxygen enters from the atmosphere; the coexistence of the two gases in certain zones of the profile creates conditions for oxidation processes, but the concentration profile, on its own, may also reflect retention, dispersion, dilution, or transport limitations. Column experiments are useful for tracking gradients and comparing materials under controlled conditions, as illustrated by Kightley *et al.* (1995) and Liu *et al.* (2024).

Geotechnical-environmental interpretation therefore requires correlating the measured concentrations with air permeability, void distribution, compaction, and the system's boundary conditions. Gebert *et al.* (2011) highlight the importance of soil physical properties for microbial oxidation in cover layers. In the present study, readings at different depths describe the spatial evolution of methane, while the detector's limit of quantification defines the level

of inference possible at the outlet locations. This distinction supports the use of “apparent attenuation” when the observed reduction does not, by itself, allow for the identification of the portion attributable to biological transformation.

2.4 WATER BEHAVIOR, POROSITY, AND MATERIAL PERFORMANCE

The purpose of this subtopic is to relate the water content and geotechnical characteristics of materials to their cover functions, particularly the balance between water retention and gas circulation. Water content alters the pore fraction occupied by air and, consequently, the transport of CH_4 and O_2; the response depends on texture, structure, degree of compaction, and changes in moisture content throughout the profile. The literature reviewed by Soares (2026) indicates that increased saturation can reduce the spaces available for gas migration, whereas moisture conditions also contribute to the environment necessary for microbial activity (Gebert *et al.*, 2011; Frasi *et al.*, 2020).

Composite materials are being investigated as components of bio-roofing due to their potentially favorable physical and physicochemical properties, but their performance must be evaluated in conjunction with their maturity, porosity, water-retention capacity, and stability. Bajwa *et al.* (2022) characterized the properties of a composite used in a green roof, while Niemczyk *et al.* (2021) discuss the potential of bio-based materials. In environmental geotechnics, comparing substrate and soil requires integrating permeability, compaction, hydrological variables, and gas profiles, avoiding the inference of overall performance based on a single parameter. This framework underpins the comparative analysis presented in this article and the relevance of simulated wetting as an evaluation condition.

3 METHODOLOGY

3.1 EXPERIMENTAL DESIGN AND MATERIALS

A comparative experimental laboratory study was conducted using two columns: one filled with sandy-clay soil from a borrow pit in Igarassu (PE) and the other with composted substrate from a composting facility, consisting mainly of fruit and vegetable waste and, to a lesser extent, commercial food waste. One column was used per material; consequently, the time-series data represent repeated measurements rather than independent experimental replicates.

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3.2 CHARACTERIZATION

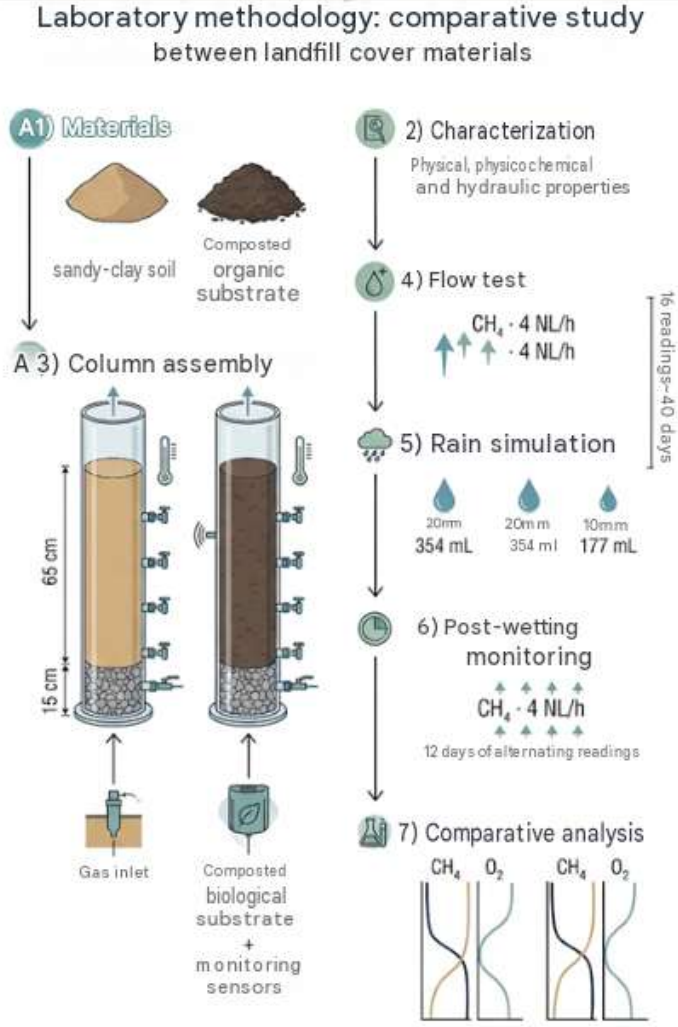
Tests were reported for particle size distribution, consistency limits, specific gravity of the grains, and Standard Proctor compaction; water and air permeability; soil water retention; optical microscopy; X-ray fluorescence; and physicochemical parameters, including pH, volatile solids, organic carbon, nitrogen, and cation exchange capacity (CEC). The filter paper suction curve was obtained only for the soil, as the substrate caused the paper to deteriorate and led to fungal growth during the equilibrium period described.

3.3 ASSEMBLY AND OPERATION OF THE COLUMNS

The PVC columns had an internal diameter of 15 cm and were 65 cm long, with a drainage base consisting of gravel, mesh, and geotextile. Each column contained four T/UR/CE sensors and four gas sampling drains. The sensors were installed at 270, 413, 613, and 730 mm from the base; the drains were located at 200, 370, 500, and 655 mm. CH_4 was continuously introduced in an upward flow of 4 NL/h for 40 days, with 16 measurement campaigns. Distilled water was then applied to simulate precipitation, and a new flow and monitoring phase began, from which 12 CH_4 concentration readings were tabulated.

Figure 1

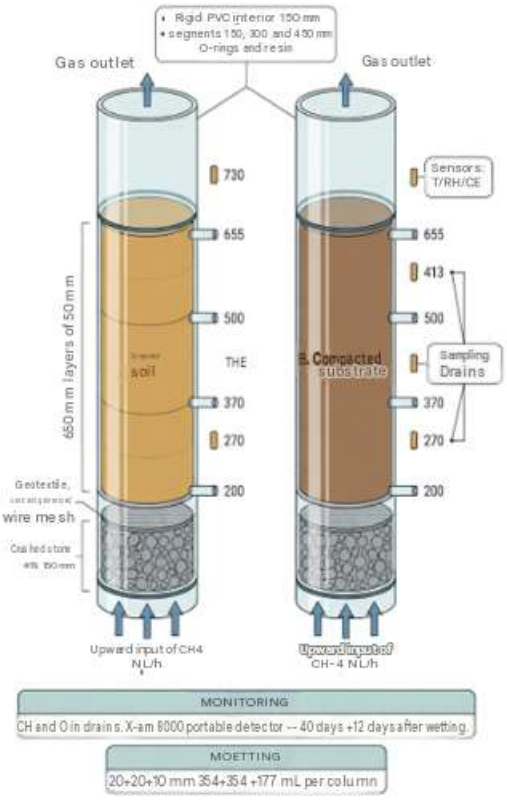
Diagram of the comparative column test and the monitored parameters



Source: Prepared for this article based on the experimental description by Soares (2026).

Figure 2

Configuration of the experimental columns and identification of the monitoring points



In both columns, the amber rectangular markers indicate temperature, relative humidity, and electrical conductivity (T/RH/EC) sensors, installed at 270, 413, 613, and 730 mm from the base. The side tubes indicate gas sampling drains, located at 200, 370, 500, and 655 mm. Column A: sandy-clay soil; Column B: composted substrate. Source: Author's own work based on Soares (2026).
Source: Prepared by the authors.

3.4 DATA PROCESSING AND LIMITATIONS OF INTERPRETATION

For each drain after moistening, the arithmetic mean and sample standard deviation were calculated from the 12 available CH_4 readings. No inferential tests were performed, as there was one column per material and the readings were time-dependent. The reported limit of quantification for the portable detector is 1% (v/v); values equal to or less than this were interpreted as unquantifiable, rather than as exact concentrations. Therefore, the observed reduction is referred to as apparent attenuation, without attributing it to confirmed oxidation.

4 R RESULTS AND DISCUSSION

4.1 COMPARATIVE PROPERTIES OF MATERIALS

The characterization reveals two materials with distinct geotechnical properties. The soil was classified in the SUCS as SC (clayey sand with low plasticity), with a liquidity limit of

27% and a plasticity index of 12%; the substrate was classified as SM (silty sand), with a liquidity limit of 48% and a plasticity index of 14%. Thus, although both contain a significant sandy fraction, they differ in terms of plasticity and response to water—aspects that are relevant for compaction, water retention, and gas transport in a cover layer.

The compaction parameters reinforce this distinction: the optimum moisture content was 10.4% for the soil and 34.5% for the substrate, and the maximum dry bulk density was 1.952 g/cm³ and 1.21 g/cm³, respectively. These values describe reference conditions obtained in the Standard Proctor test and help to understand differences in structure and density between the materials. They do not, on their own, constitute criteria for superiority: their significance depends on the condition actually achieved in the column and on the interaction between porosity, moisture content, and permeability.

Table 1

Selected properties reported for the tested materials

Parameter	Sandy-clay soil	Comported substrate
SUCS classsification	SC — clayey sand	SM — silty sand
Liquidity Limit, LL (%)	27	48
Plasticity Index, IP (%)	12	14
Proctor Optimun Moisture (%)	10,4	34,5
Maximum Dry ssBulk Density (g/cm³)	1,952	1,21
Water permeability (m/s)	$9{,}51 \times 10^{-7}$	$1{,}83 \times 10^{-8}$
Reported H	Not listed in the table consulted	9
Total Kjedahl Nitrogen (%)	1,04	2,97
Total Organic Carbon (%)	0,655	0,238
Total Organic Matter (%)	1,129	0,410
Loss on Ignition (%)	9,15	30,64
CTC (mmolc/kg)	29,248	282,727
Volatile Solids (%)	—	21

CTC = cation exchange capacity; SUCS = Unified Soil Classification System. "—" = not reported for this material. Source: Soares (2026), characterization and compaction tables.
Source: Prepared by the authors.

The hydraulic conductivity for water reported for the substrate (1.83×10^{-8} m/s) was approximately 52 times lower than that of the soil (9.51×10^{-7} m/s), a ratio calculated from the values presented in the dissertation. This contrast indicates distinct responses to water flow, but should not be taken as a direct measure of air permeability: gas transport also depends on pore connectivity and the degree of saturation. In the air permeability tests, the description indicates higher flow in the soil under certain pressures, without a complete numerical series that would allow for a further quantitative comparison. The physicochemical indicators add relevant dimensions to the comparison. The substrate showed higher reported values for total Kjeldahl nitrogen (2.97% versus 1.04% in the soil) and cation exchange

capacity (282.727 contra 29,248 mmolc/kg), properties relevant to nutrient retention and material characterization. In contrast, the tables in the dissertation show lower total organic carbon and total organic matter in the substrate than in the soil, while the loss on ignition was higher in the substrate (30.64% versus 9.15%). Since these indicators are not interchangeable and the results point in different directions, the appropriate interpretation is an integrated one, without reducing organic composition to a single measure.

Taken together, the characterization results show why the evaluation of a soil cover cannot be based on a single property. The substrate's lower hydraulic conductivity, higher optimum moisture content, and higher CTC and nitrogen values result in a profile that differs from that of sandy-clay soil; at the same time, maximum dry density, plasticity, and organic matter indicators introduce differences that must be considered in the design and performance evaluation. This comparative analysis establishes the basis for interpreting the methane profiles and the response to wetting presented in the following sections.

4.2 METHANE PROFILES BEFORE MOISTENING

During continuous flow, the narrative records indicate a high concentration of CH_4 in the lower drain and a decrease toward the upper drains. For the period prior to wetting, the study reports an average apparent removal of 88.4% for the substrate and 93% for the soil. The text itself attributes the predominant role in the soil to physical retention mechanisms and acknowledges that the decrease in concentration and the presence of O_2 do not, on their own, confirm methanotrophic activity. Therefore, these percentages describe the attenuation measured under the experimental setup, not demonstrated rates of oxidation. This caution aligns with studies that identify the process's dependence on moisture, oxygen transport, and the structure of the soil or compost (Gebert *et al.*, 2011; Frasi *et al.*, 2020). The lack of microbiological confirmation in the study and the use of a single column section per material limit causal attribution and the generalizability of the percentages.

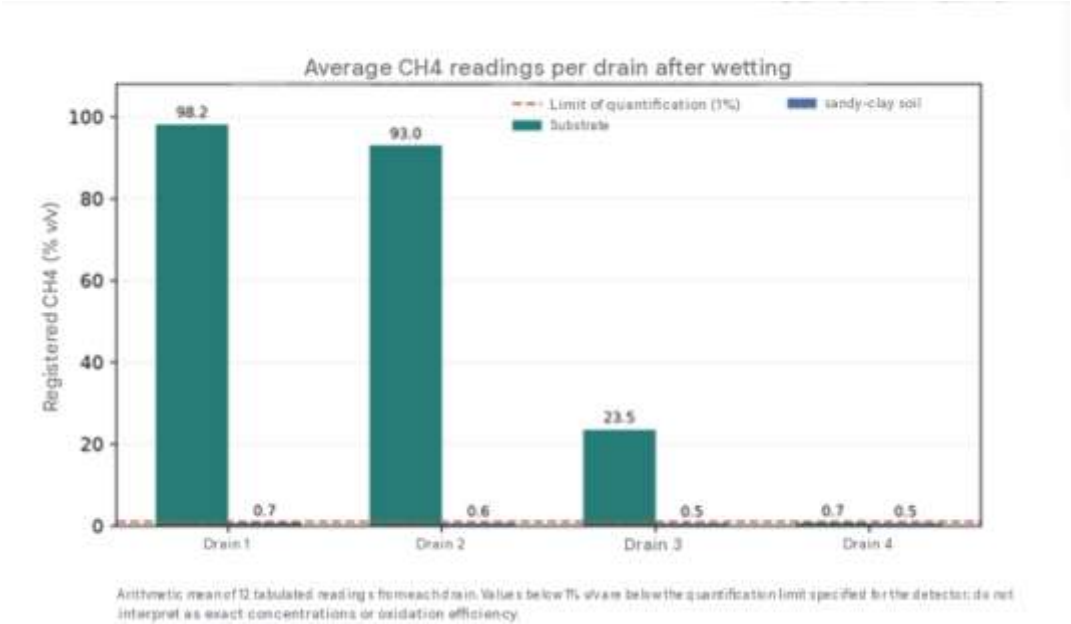
4.3 RESPONSE AFTER SIMULATED WETTING

The table of 12 post-wetting campaigns summarizes the readings by drain. In the substrate, the recorded average drops from 98.17% in drain 1 to 0.66% in drain 4; in the soil, the tabulated averages range from 0.53% to 0.72%. However, virtually all observations in the substrate outlet drain and all those in the soil are at or below the limit of quantification reported for the detector. Thus, mean values below the LOQ should not be interpreted as exact

quantitative measurements, and converting them to removal percentages may amplify the uncertainty.

Figure 3

Average CH_4 concentration recorded in each drain after moistening



Sample mean and standard deviation of 12 tabulated readings per drain. Dotted line = limit of quantification specified for the detector (1% v/v). Values below this limit do not represent exact quantifications. Source: descriptive calculation based on Soares (2026), table of post-wetting concentrations.
Source: Prepared by the authors.

Table 2

Descriptive statistics for the 12 post-moistening readings per drain

Material	Drain 1	Drain 2	Drain 3	Drain 4
Substrate	98,17 ± 1,40	93,00 ± 8,46	23,54 ± 17,97	0,66 ± 0,17
Sandy-clay soil	0,72 ± 0,20	0,59 ± 0,11	0,53 ± 0,08	0,55 ± 0,09

Note. Data are expressed as % v/v, mean ± sample standard deviation, n = 12 time-series readings per data point. Limit of quantification: 1% v/v; results equal to or below this limit should be interpreted with caution.
Source: Prepared by the authors.

Note. Data are expressed as % v/v, mean ± sample standard deviation, n = 12 time-series readings per data point. Limit of quantification: 1% v/v; results equal to or below this limit should be interpreted with caution. Source: descriptive calculations based on Soares (2026).

The study reports, after moistening, apparent removal estimates of 99.33% for the substrate and 22.42% for the soil. These values should be interpreted with caution: the table shows soil readings between 0.4% and 1.0% in the four drains, and the surface values for

the substrate are also concentrated around or below 1%. The discrepancy between the readings below the quantification threshold, the description of the moistening process, and the derived estimates prevents these percentages from being treated as precise evidence of oxidation. In the substrate, the preservation of O_2 near atmospheric levels at the surface and the decline in CH_4 are consistent with potentially favorable conditions, but do not prove biological conversion without a validated mass balance or microbiological characterization.

The role of water is not straightforward: moistening can promote microbial activity by reducing dryness, but the filling of pores simultaneously limits gas diffusion. In the study, sensors recorded higher moisture content in the substrate (approximately 18.5%–31% before moistening, as reported) and about 9.5%–13.6% in the soil. After the event, the reported moisture content remained higher in the substrate, while the soil exhibited a low measurable CH_4 flux. This response is consistent with the possibility of physical blocking or retardation, but instrumental quantification below the LOQ does not allow for quantifying the magnitude of the effect (Gebert *et al.*, 2011; Frasi *et al.*, 2020).

4.4 INTERPRETIVE SYNTHESIS AND CONTRIBUTION TO ENVIRONMENTAL GEOTECHNICS

Taken together, the results show that the behavior of the layers depends on a combination of composition, structure, moisture content, and gas transport. The comparison highlights distinct CH_4 profiles and contrasting moisture conditions, providing useful information to guide studies of cover materials in environmental geotechnics. Estimates associated with readings near or below the limit of quantification are presented as apparent attenuation; the distinction between this pattern and the demonstration of a specific mechanism strictly defines the scope of the results.

The wetting stage underscores the importance of characterizing the water regime in the evaluation of cover materials: water can promote biological conditions within certain ranges and, at the same time, alter gas diffusion. The joint monitoring of CH_4, O_2, moisture, temperature, and electrical conductivity constitutes a methodological contribution of this study toward future laboratory comparisons and the selection of relevant variables in environmental geotechnical studies.

The key finding consists of an integrated experimental comparison of a local sandy-clay soil and a composted substrate, with gas profiles monitored before and after moistening.

The findings support the continued evaluation of alternative materials for mulch and provide insights for applied research, while limiting the interpretation to the laboratory scale.

5 CONCLUSION

The experimental comparison aimed to evaluate the behavior of a sandy-clay soil layer and a layer of composted substrate under an upward CH_4 flux and simulated wetting. In both columns, the monitored profiles showed a decrease in methane concentration toward the upper positions, with distinct responses between materials and test stages. Before moistening, the dissertation reported average attenuation estimates of 93% for the soil and 88.4% for the substrate; after moistening, estimates of 22.42% and 99.33% were reported, respectively. These values characterize the apparent behavior under the test conditions and do not represent a confirmed oxidation rate.

A joint analysis of geotechnical properties, gases, and environmental variables highlighted the importance of the water regime and the structure of the porous medium in interpreting the performance of the cover layers. The differences observed between optimum moisture content, maximum dry bulk density, hydraulic conductivity for water, and physicochemical parameters help contextualize the CH_4 profiles and the response to wetting, without attributing exclusive causality to a single factor. The key contribution to environmental geotechnics lies in integrating material characterization and in-situ monitoring to enable a traceable comparison applicable to the study of cover layers.

Composted substrate stands out as a promising alternative for further evaluation of cover materials, while sandy-clay soil provides a comparative reference of geotechnical interest. The study's definitive conclusion is that both materials exhibited apparent methane attenuation capacity in the laboratory setup, and that the observed intensity varied depending on the material and moisture conditions. Since some of the output readings were at or below the detector's limit of quantification, the percentages should be interpreted within this metrological framework; taken in isolation, they do not demonstrate biological conversion of CH_4 or performance on a landfill scale.

The results provide insights for the development of criteria for selecting and evaluating materials in environmental geotechnics by identifying variables that should be considered collectively: compaction properties, permeability, moisture content, temperature, electrical conductivity, and CH_4 and O_2 profiles. The research also establishes a comparative basis for subsequent pilot-scale and field-scale stages, in which the confirmation of mechanisms and

performance evaluation can be further explored. Thus, this work contributes to the agenda of reducing GHG emissions by producing relevant experimental evidence that is limited to the scope actually investigated.

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