

Performance of geosynthetics in methane oxidation systems

Vanessa Di Battista^{1*}, Sophie Filion², and Alexandre R. Cabral¹

¹Université de Sherbrooke, Département de génie civil et du bâtiment. Sherbrooke, Canada

²Carleton University, Department of Civil & Environmental Engineering, Ontario, Canada

Abstract. Landfills are a major source of methane emissions contributing to climate change. These emissions can be fugitive emissions from capped landfills, where hotspots form due to vulnerabilities (e.g., holes, fissures) in the cover. A research project investigating the use of “biowindows” for the biological oxidation of methane has been initiated by the Université de Sherbrooke. This study will examine the performance of geosynthetic drainage composite as a gas distribution layer (GDL) and a wicking geotextile as a separation layer between the methane oxidation layer and GDL. This study is a pilot scale installation with ten 2 m x 2 m biowindows fed directly by landfill gas. As occlusion due to moisture retention is a major impediment to gas transport and system efficiency, this study examines the inclusion of geosynthetics and their effects on gas transport and system efficiency.

1 Introduction

Wicking geotextiles have been proposed for road applications as they permit the drainage of ponded water in subgrades, reducing porewater pressures and the risk of displacements [1](Wicking geotextiles are woven geotextiles that contain fibres that are hydrophilic and hygroscopic. These fibres draw water from the surrounding environment to the geotextile, permit water migration by gravity, and will release the water through evaporation[2]. While wicking geotextiles are primarily used in road construction, their ability to remove pore water from adjacent soils can be beneficial for methane oxidation biosystems constructed in landfill covers.

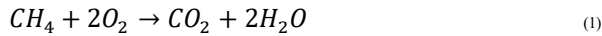
Landfill cover systems serve two important environmental containment purposes – controlling infiltration and controlling the emissions of landfill gases. During decomposition of the organic fraction of waste materials, gases are produced as biproduct; this is referred to as landfill gas. A major component of landfill gas is methane (CH₄), which composes approximately 50%-60% of gas composition[3]. CH₄ is the gas of primary concern as it has a higher global warming potential (84 over 20 years) compared to CO₂ [3,4]. Collection and treatment of landfill gas to produce bioenergy is a common practice while the CH₄ concentrations are high enough to generate energy. However, even with energy recovery systems in use, the waste management sector accounts for over 20% of CH₄ emissions in Canada [3,5–9]

Methane emissions, which can last up to 100 years, from landfills are present during the active gas collection period and once gas collection has ceased[10,11]. These emissions can be a

* Corresponding author: vanessa.di.battista@usherbrooke.ca

result of venting systems and vulnerabilities in the cover. Possible vulnerabilities that would result in fugitive methane are access points or cracks that develop in the cover due to displacement with time (e.g., tension cracks in compacted clay liners). These vulnerabilities create a preferential flow path for gas transport in the low permeability cover materials resulting in hotspots of high methane concentrations.

Biosystems within final cover systems have been developed as a passive method of treating landfill gas to oxidize the CH₄ to CO₂, reducing the global warming potential of the gas to 20-80 times less than that of CH₄, thus decreasing greenhouse gas emissions [3]. Biosystem uses methanotrophs naturally found in the environment to oxidize methane for metabolic energy, producing CO₂, as shown in Equation 1[12].



Biosystems consist of two main parts: a gas distribution layer (GDL) and a methane oxidation layer (MOL). The main component in these systems is the methane oxidation layer (MOL). The GDL predominately serves the primary function of distributing the gas along the MOL/GDL interface, secondarily as drainage layer to avoid build-up of water from infiltration and created by the methane oxidation reaction.

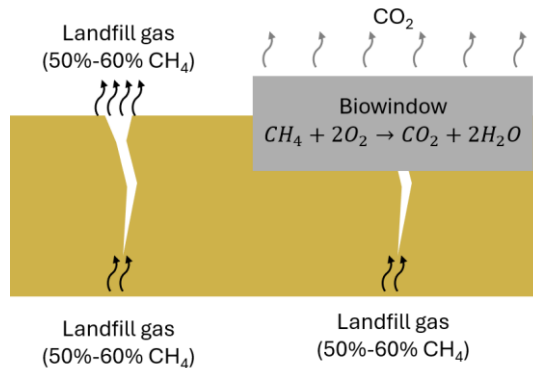


Fig. 1. Conceptual model of biowindow system in cover context

To reduce CH₄ emissions from landfills, the installation biowindows within final cover systems has been proposed [3]. Biowindows are a term used for biosystems installed to intercept landfill gas emissions from hotspots, thus using a pre-existing defect as a preferential flow path towards the biosystem. This plan seeks to use existing hotspots to direct methane to the treatment system without changing operating conditions. (Figure 1). The proposed design of a biowindow is to excavate material located at the hotspot and install a methane oxidation biosystem. It is not necessary to completely remove the cover (Figure 1), but rather excavate just enough material to install a functioning biosystem.

Hydraulics of biosystems is an important design consideration as the presence of water will occlude gas transport and reduce the available methane for oxidation. Thus, a major concern with biosystems is the creation of a capillary break at the interface of the MOL and the GDL. A capillary break can form when finer material overlays coarse material causing suction in the finer material pores to hold water at a high degree of saturation until a degree of saturation is reached where matric suction is reduced to a level that allows the release of the pore water. This has been observed in previous studies of biosystems (13). These types of highly saturated areas of the MOL can restrict gas migration. Thus, a parameter of the length of unrestricted gas migration (LUGM) has been proposed in the design of these systems[13]. Occlusion is said to occur when the water content of the MOL is higher than that of the occlusion water content. The occlusion water content

is defined using laboratory tests to measure the water content at which the gas permeability of the material significantly decreases (14). Dulac et al (2024) determined the occlusion volumetric water contents to be 55% for their MOL compost matrix[13].

Current biosystem design methods for biosystems use readily available materials. Gravels similar to those used in leachate collection systems are proposed for the GDL, and valorized waste materials such as compost mixes are sometimes used for the MOL (10,13). While geotextiles have been used in the construction of biosystems, their use has been for the separation of layers and not to provide any hydraulic or gas distribution benefit. This project investigates the inclusion of geosynthetics in the design of methane oxidation biosystems and their impacts on the system hydraulics and methane oxidation efficiency. The present article provides early laboratory and field data to develop preliminary conclusions of the benefits of using two different combinations of geosynthetics for the GDL from a hydraulics standpoint.

2 Methods

An experimental test site was constructed at the Bury landfill (Bury Québec, Canada). The site consists of 10 biowindows, where five are constructed using conventional materials for the GDL and five are constructed using geosynthetics for the GDL (Figure 2). The biowindows were constructed into a simulated cover consisting of clay material meeting the applicable regulations for landfill covers [15]. The MOL has a thickness of 1 m. The GDL on the conventional (Conv) design side is composed of 0.3 m gravel and with a non-woven geotextile filter to prevent loss of fines from the MOL into the GDL. The GDL on the geosynthetics side (Geo) is constructed with a geocomposite drain (GCD), Fabrinet DTX (Solmax). The GCD is an 8.4 mm-thick geonet sandwiched between two 200 g/m² nonwoven geotextiles (NW-GTX). Additionally, a wicking woven geotextile (WW-GTX), H₂Ri (same company as DTX), was installed above the GCD. The subgrade slope where the GDLs were installed was 6%. While this project focuses only on the hydraulics of the system, another major research question of the project is the efficacy of the GCD as a GDL compared to 0.3 m of gravel.

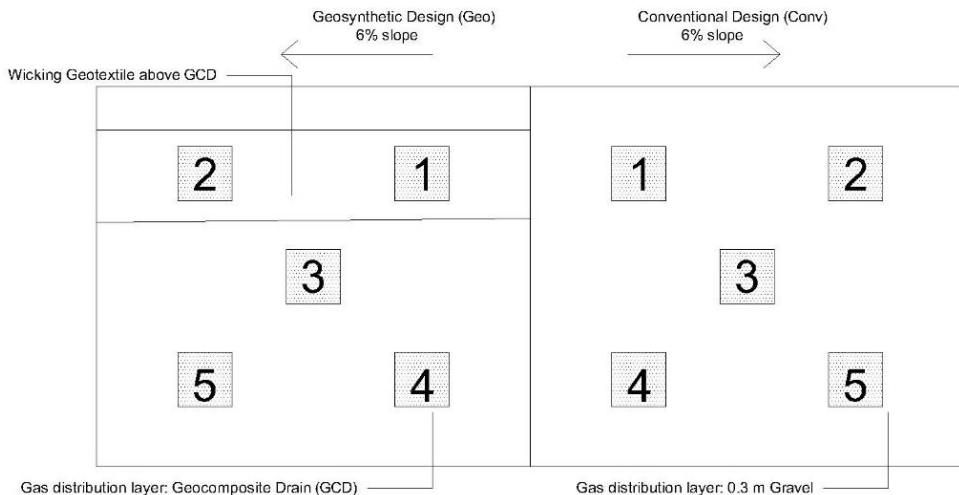


Fig. 2. Plan view of biowindow test site where biowindows on the left side are denoted as “Geo” and biowindows on the right side are denoted as “Conv”

The WW-GTX has bidirectional highly porous fibres that preferentially wick water. These fibres are installed in the cross-machine direction as these materials are typically associated with wicking water to the edges of roads. The WW-GTX was installed to align the wicking fibres with

subgrade slope, to permit wicking in the direction of flow. This geotextile has been studied by (2023)[16].

Each biowindow was instrumented with five moisture content sensors (Figure 3). Teros10 (METER Group) capacitance moisture content sensors were placed at a depth of 90 cm at the upslope and downslope edges of the biowindow. While Teros11 sensors (METER Group) were placed in the centre of the biowindow at depths of 45 cm, 70 cm and 90 cm. These sensors will collect moisture content (Teros 10 and Teros11) and temperature (Teros11) during the project testing phase; however, the present paper focuses on data collected from the Teros10 sensors only. These sensors have been collecting data since construction (August 2024), and calibration developed in-lab using the MOL material has been applied to the sensor readings. As the data collection is occurring prior to the connection to a methane source, moisture content fluctuations are a result of precipitation only, not metabolic water generation due to methane oxidation.

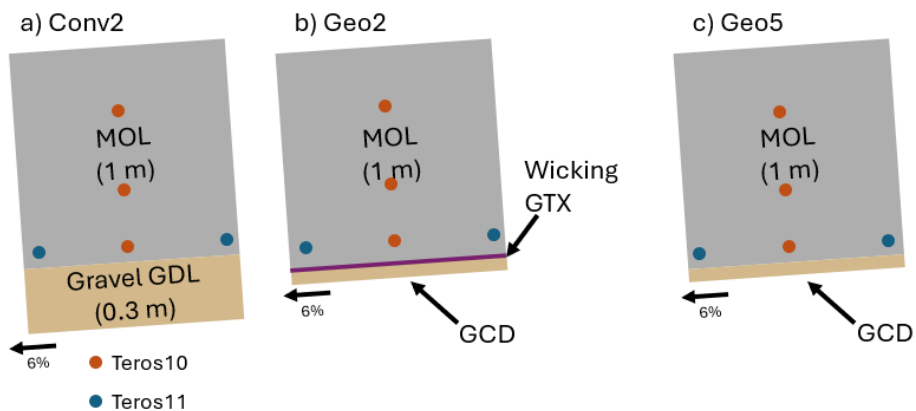


Fig. 3. Profile schematics of the three biowindow constructions studied with sensor placement; (a) Conv2, (b) Geo2, (c) Geo5 (MOL thickness = 1 m)

Laboratory investigation of the water retention curve using the NW-GTX from the GCD and WW-GTX was conducted using the hanging column method to establish the in-plane wetting curve. Dry 500-mm strips of geotextile were wrapped in a plastic wrap to prevent evaporation were hung until equilibrium (3 days) with the bottom of the strip submerged in water[17]. After equilibrium had been reached, the strips were cut into 20 mm slices to evaluate the gravimetric moisture content at varying heights above the free water surface. Suction (ψ ; kPa) was then calculated using the following relationship (Equation 2):

$$\psi = h\rho g \quad (2)$$

where h represents the height [m] above the free water surface, ρ is the density of water (1 Mg/m³ was assumed), and g is the acceleration due to gravity (9.8 m/s²). For each 20 mm strip, the gravimetric water contents (w) were calculated and plotted with the respect to the suction calculated for the mid-point height of the section. These plots were then used to propose a residual water content (w_r) and a normalized saturation (Θ_{ng}) calculated using Equation 3:

$$\Theta_{ng} = \frac{w-w_r}{w_s-w_r} \quad (3)$$

where w_s represents the saturated water content. Least squares regression was then performed to propose van Genuchten (1980) parameters a [1/kPa] and n [-] using Equations 4 and 5:

$$\Theta_{ng} = \frac{1}{[1+(a\psi)^n]^m} \tag{4}$$

$$m = 1 - \frac{1}{n} \tag{5}$$

3 Results and discussion

3.1 Laboratory results

Using the hanging column method, wetting curves were developed for the two geotextiles (Figures 4 and 5), and van Genuchten (1980) parameters for the materials are summarized in Table 1.

Table 1. van Genuchten (1980) fitting parameters for the wetting curves of NW-GTX and WW-GTX

	<i>a</i>	<i>n</i>	<i>m</i>
	(1/kPa)	(-)	(-)
NW-GTX	5.64	4.18	0.76
WW-GTX	1.52	2.32	0.57

The wetting curve was the focus of interest as the likelihood of a capillary break forming between the MOL and the geotextile is governed by the relationship of the water entry suction (ψ_{WEV}) of the geotextile and the air entry suction (ψ_{AEV}) of the MOL. As summarized in Table 2, a soil matrix with a ψ_{AEV} higher than that of the underlying GDL or geotextile will be more likely to develop occlusion.

Table 2. Summary of suction relationships between the MOL and GDL

$\psi_{WEV_{GDL/GTX}} < \psi_{AEV_{MOL}}$	Capillary break forms, MOL has a higher likelihood of occlusion
$\psi_{WEV_{GDL/GTX}} > \psi_{AEV_{MOL}}$	Moisture migrates from the MOL to the layer below

The experimental results (Figure 4) from the hanging column test of NW-GTX showed that, for the ranges of suctions attainable with the testing method, the water contents ranged from w_s to beyond w_r . Using the experimental data and the van Genuchten (1980) parameters developed through least squares regression (Table 1), values of 0.47 kPa and 0.085 kPa have been proposed for ψ_{WEV} and ψ_{AEV} , respectively (Table 3). Experimental results for WW-GTX (Figure 5) show that for the suction ranges attainable with the hanging column method, it is unclear whether the w_r was truly reached, as the characteristic constant stable water content was not observed for a wide range of suctions. Using the experimental data and the van Genuchten (1980) parameters developed through least squares regression (Table 1), values of 3.3 kPa and 0.26 kPa have been proposed for ψ_{WEV} and ψ_{AEV} , respectively (Table 3).

With respect to NW-GTX, the hanging column has significant limitations for developing a complete water retention curve, as the suctions available are lower than those required to release all non-irreducible water from the geotextile. This means that this method likely underestimates the water entry suction and is likely conservative. It is evident that to fully capture the suction range of a wicking geotextile, which will preferentially draw moisture from the environment, several methods of assessment are required, as shown in [16].

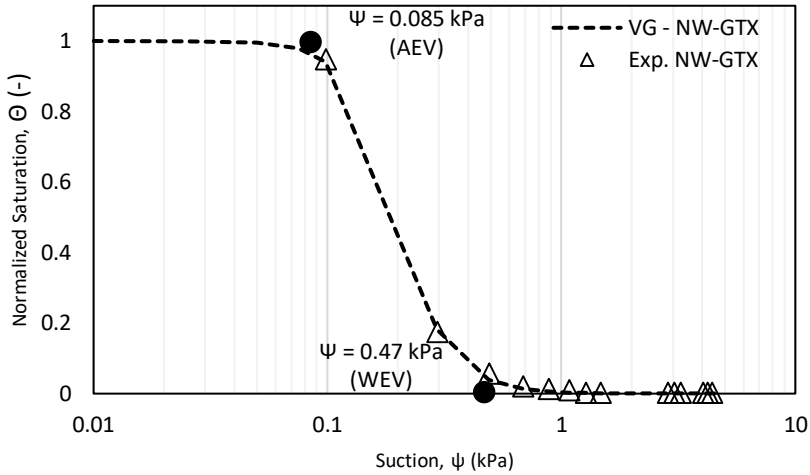


Fig. 4. Experimental and theoretical water retention curve of NW-GTX under wetting conditions

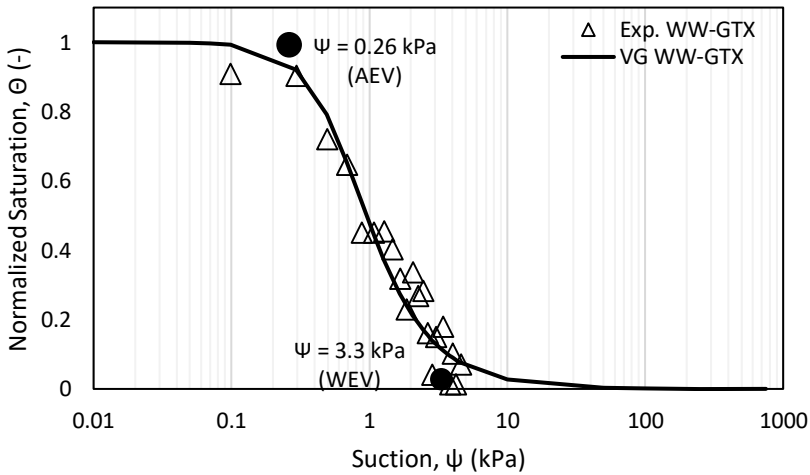


Fig. 5. Experimental and theoretical water retention curve of WW-GTX under wetting conditions

These preliminary findings can be applied to the biowindows to hypothesize the behaviour of water at the MOL/GDL interface for a novel construction using a GCD or a GCD overlain by a wicking geotextile compared to a gravel GCD. Based on findings from Dulac et al (2024), it is expected that the compost material used in the MOL will have ψ_{AEV} values ranging from 0.2 kPa to 0.6 kPa (13). If this material overlies a gravel material (ψ_{WEV} 0.1 kPa to 0.7 kPa, depending on the grain size), it is likely that water will be preferentially retained by the MOL until the water content is sufficiently high to decrease the suction to lower than the ψ_{WEV} of gravel (Table 3). Higher water contents in the MOL will increase the likelihood of occlusion of the GDL and limiting methane migration into the MOL, as observed by [13,18]. The same is likely true for the GCD with the non-woven geotextile, as the ψ_{WEV} is lower than that of the ψ_{AEV} of the compost material. However, when a wicking geotextile is placed beneath MOL, the value of the ψ_{WEV} is at least an order of magnitude higher than that of the compost, thus water will preferentially enter

the wicking fibres of the geotextile, and the chances of occlusion can be diminished. Thus, inclusion of this type of geotextile has the potential to increase the LUGM in methane oxidation systems and increase the oxidation of CH₄ to CO₂ by the system.

Table 3. Summary of water entry suctions of gravel, NW-GTX, and WW-GTX compared to air entry suctions of MOL material

	ψ_{WEV}	ψ_{AEV}
Gravel ^a	0.1 – 0.7 kPa	-
NW-GTX	0.47 kPa	-
WW-GTX	3.3 kPa	-
MOL ^b	-	0.2 to 0.6 kPa

3.2 Preliminary sensor data

At the time of writing, volumetric water content sensors collected data from 15 August 2024 to 9 November 2024. During this time, the biowindows have remained uncovered and susceptible to infiltration. The sensor data provides a preliminary comparison of hydraulic response of the three MOL/GDL interface conditions (Figure 6). Conv2, Geo2, and Geo5 (Figure 2) have been selected as they are positioned closest to the downslope edge of the experimental test site with the only difference being interface MOL/GDL interface (Figure 3).

During this preliminary monitoring period, the following trend was observed for in the downslope sensors: $\theta_{Geo5} > \theta_{Geo2} > \theta_{Conv2}$, with Geo2 and Geo5 showing higher moisture contents than their upstream counterparts. This is to be expected as moisture will migrate from high head to lower head and collect on the downslope edge. However, Conv2 did not show this trend, as the volumetric water content of the upslope sensor often surpassed that of the downslope sensor, and the mean values were nearly equal with values of 35.0% (downslope) and 35.2% (upslope). In contrast, the differences of the means were more pronounced for Geo2 and Geo5, with values over 5% and 14%, respectively.

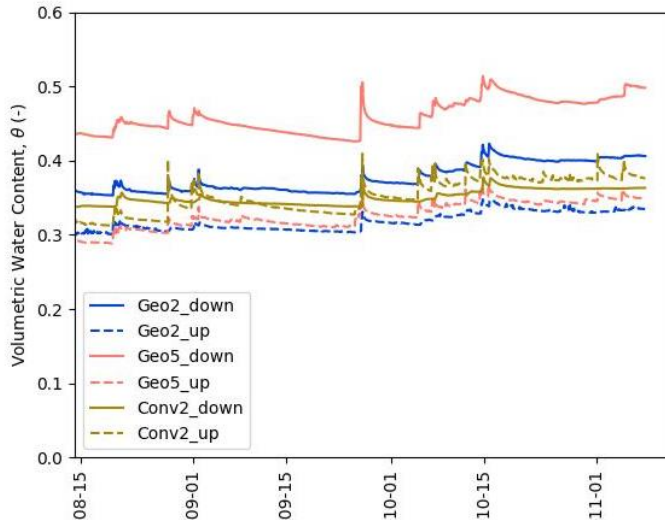


Fig. 6. Volumetric water content with respect to date (2024) as recorded by Teros10 sensors

Table 4. Summary of average volumetric moisture contents upslope and downslope for the three biowindows

Biowindow ID		Average downslope θ	Average upslope θ
Geo2	GCD + wicking GTX	37.6%	31.8%
Geo5	GCD only	46.0%	32.6%
Conv2	0.3 m gravel + separation GTX	35.0%	35.2%

The hydraulic responses of the different constructions can impact the methane oxidation efficiencies. As a more uniform response was exhibited along the length of Conv2, one concern is that water content will increase uniformly while methane oxidation occurs due to the metabolic water produced in the reaction (Equation 1), resulting in a uniformly occluded biowindow. In contrast, Geo2 and Geo5 exhibit the expected higher moisture contents at the downslope edge, but the upslope edge has lower moisture contents, as measured by the sensors. This suggests that with the addition of metabolic water produced by the methane oxidation reaction, there will be more occlusion at the downslope edge, but upslope may remain below the occlusion threshold and allow the migration of gas to the MOL, increasing efficiency. Currently, these are hypothesized responses and need verification through analysis of gas concentrations at varying depths in the biowindows and flux chamber measurements.

4 Conclusions

Based on experimental data and sensor data from the field site, the following preliminary conclusions are proposed:

1. Preliminary results of water retention curves indicate water entry value for the wicking geotextile is 3.3 kPa compared to 0.47 for the non-woven geotextile present in the GCD. When in contact with the compost layer, the wicking geotextile will be able to pull water from the compost layer, potentially reducing the LUGM.
2. Sensor results from the experimental test site show that MOL/GDL interface construction creates a varied hydraulic response in the MOL layer. Notably, the conventional construction with MOL/GTX/gravel produces a uniform moisture content along the length of the biowindow. In contrast, for the GDL constructed using geosynthetics, higher moisture contents were recorded at the downslope edges of the biowindows, while there was decreased moisture contents recorded at the upslope edges of the biowindows. This indicates that the geosynthetics GDL constructions may increase the LUGM and increase methane oxidation efficiencies.

These results are preliminary, and further testing will be performed to evaluate the performance of the materials in the context of the methane oxidation system.

Funding: NSERC (ALLRP 586235), Valoris, Environment and Climate Change Canada, Dillon Consulting Ltd., and Region of Waterloo.

Acknowledgements: The authors gratefully acknowledge technical contributions by M. Duarte Neto and Y. Dulac, logistics support from Valoris, and Solmax for providing materials and technical advice in developing the geosynthetic research plan.

Author contributions: *V. Di Battista:* Conceptualization, Formal analysis, Methodology, Resources, visualization, Writing – original draft, Writing – review and editing, Supervision. *S. Filion:* Investigation, Formal analysis, Data visualization. *A.R. Cabral:* Conceptualization, Project administration, Resources, Funding acquisition, Writing – review and editing.

References

1. Zhang X, Presler W, Li L, Jones D, Odgers B. Use of Wicking Fabric to Help Prevent Frost Boils in Alaskan Pavements. *J Mater Civ Eng*. 2014 Apr; 26(4): 728–40.
2. Wang F, Han J, Zhang X, Guo J. Laboratory tests to evaluate effectiveness of wicking geotextile in soil moisture reduction. *Geotextiles and Geomembranes*. 2017 Feb; 45(1): 8–13.
3. Gebert J, Huber-Humer M, Cabral AR. Design of Microbial Methane Oxidation Systems for Landfills. *Front Environ Sci*. 2022 Sep 1; 10. Available from: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.907562>
4. Saunio M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, et al. The Global Methane Budget 2000–2017. *Atmosphere – Atmospheric Chemistry and Physics*; 2019. Available from: <https://essd.copernicus.org/preprints/essd-2019-128/essd-2019-128.pdf>
5. Statistics Canada. Human Activity and the Environment: Waste management in Canada. Ottawa; 2012. Available from: www.statcan.gc.ca,
6. Government of Canada. Municipal solid waste and greenhouse gases. 2017. Available from: <https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/greenhouse-gases.html>
7. Environment and Climate Change Canada. Canadian Environmental Sustainability Indicators: Greenhouse gas emissions from large facilities. 2022.
8. Environment and Climate Change Canada. Reducing methane emissions from Canada’s municipal solid waste landfills. 2022. Report No.: EC21285.
9. Environment and Climate Change Canada. 2030 EMISSIONS REDUCTION PLAN Canada’s Next Steps for Clean Air and a Strong Economy. Ottawa: Government of Canada; 2022.
10. Nelson B, Zytner RG, Dulac Y, Cabral AR. Mitigating fugitive methane emissions from closed landfills: A pilot-scale field study. *Science of The Total Environment*. 2022 Dec; 851:158351.
11. Huber-Humer M, Röder S, Lechner P. Approaches to assess biocover performance on landfills. *Waste Management*. 2009 Jul; 29(7):2092–104.
12. Huber-Humer M, Gebert J, Hilger H. Biotic systems to mitigate landfill methane emissions. *Waste Manag Res*. 2008 Feb; 26(1):33–46.
13. Dulac Y, Nelson BR, Zytner RG, Cabral AR. Validation of a methane oxidation biosystem design methodology using numerical modeling. *Front Environ Sci*. 2024 Jul 30; 12:1397134.
14. Athoughalandari B, Cabral AR. Landfill gas distribution at the base of passive methane oxidation biosystems: Transient state analysis of several configurations. *Waste Management*. 2017 Nov; 69:298–314.
15. Gouvernement du Québec. Règlement sur l’enfouissement et l’incinération de matières résiduelles [Internet]. Loi sur la qualité de l’environnement. Sect. Q-2, r. 19 Jul 1, 2024. Available from: <http://legisquebec.gouv.qc.ca/fr/showdoc/cr/Q-2, r. 19>
16. Lin C, Guo Y, Zhang X, Galinmoghadam J. Reexamination of traditional testing techniques for determining WRCs of woven geotextiles in full suction range. *Geotextiles and Geomembranes*. 2023; 51:1–16.
17. Zornberg JG, Bouazza A, McCartney JS. Geosynthetic capillary barriers: Current state of knowledge. *Geosynthetics International*. 2010; 17(5):273–300.
18. Tokunaga TK, Wan J, Olson KR. Saturation-matric potential relations in gravel. *Water Resources Research*. 2002 Oct; 38(10). Available from: <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001WR001242>