Energy Potential of Biomethane from Municipal Solid Waste in Brazilian Cities Using an Adjusted LandGEM Approach

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Sanitary landfills for municipal solid waste (MSW) represent a significant and still underutilized source of renewable energy, especially in developing countries where disposal in dumpsites and landfills remains the primary form of final waste disposition. Brazil presents favorable conditions for the utilization of landfill biomethane due to the high organic matter content of its MSW and its tropical climate, which intensifies anaerobic degradation rates. This study evaluates methane generation and the energy recovery potential associated with MSW disposal in two Brazilian municipalities — Salvador and Feira de Santana — using a first-order decay model based on the LandGEM methodology from the United States Environmental Protection Agency (USEPA). Model parameters were adjusted to Brazilian conditions, adopting a methane generation potential (L_0) of 170 m^3 CH_4/Mg MSW and a decay constant (k) of 0.05 yr^{-1} for both Feira de Santana (tropical climate) and Salvador (tropical super-humid climate), both classified as non-arid according to the LandGEM criterion. Historical waste collection data and future projections, assuming an annual growth rate of 5%, were used to estimate methane generation until 2062 for Salvador and until 2075 for Feira de Santana, adopting the 80-year operational lifetime established by LandGEM. The results indicate a peak methane generation of 2.5×10^8 m^3 CH_4/year and a total of 5.9×10^9 m^3 CH_4 for the analyzed period, corresponding to electricity generation potentials of 49 MW. This demonstrates that landfill biomethane utilization can significantly contribute to Brazil's renewable energy matrix, substituting natural gas, and highlights the importance of integrating waste-to-energy solutions into national energy policies.

Keywords: Landfill Gas. Municipal Solid Waste. Biomethane. Renewable Energy. Greenhouse Gases. Brazil.

Municipal solid waste (MSW) management remains one of the main environmental and socioeconomic challenges on a global scale, particularly in rapidly urbanizing regions of developing countries. Despite advances in recycling and material recovery, disposal in sanitary landfills continues to be the primary form of final waste disposition in many countries.

One of the main environmental concerns associated with landfills is the generation of methane (CH_4), considered a potent greenhouse gas (GHG) with a global warming potential 25 times greater than that of carbon dioxide (CO_2) over a 100-year period [1].

However, the utilization of methane for energy generation presents beneficial environmental and economic effects. The combustion of methane (CH_4) produces heat, water, and CO_2. From an environmental perspective, burning methane to generate energy reduces GHG emissions due to methane's global warming potential being higher than that of CO_2 [2]. The combustion of methane in the energy generation process is sustainable from a GHG standpoint, as it substantially reduces CO_2-equivalent emissions into the atmosphere. From an economic viewpoint, biomethane produced in sanitary landfills is a fuel that can substitute natural gas (NG), with the advantage of being renewable (Renewable Natural Gas - RNG) and produced from residual raw material (MSW).

Methane emissions from landfills result from the anaerobic decomposition of the biodegradable organic fraction present in MSW. According to the Intergovernmental Panel on Climate Change (IPCC), landfills account for a relevant portion of global anthropogenic methane emissions, making them a

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strategic target for mitigation actions. At the same time, landfill biomethane constitutes a valuable energy resource that can be recovered and converted into electricity, heat, or purified to biomethane for injection into natural gas networks or use as vehicle fuel [2,3].

Brazil presents a particularly favorable context for landfill biomethane utilization. The country's municipal solid waste is characterized by a high organic matter content, typically between 45% and 55% [2,4], combined with climatic conditions of high temperature and humidity. These factors accelerate biodegradation processes and increase methane generation rates compared to temperate climate regions. Despite this potential, landfill biomethane energy recovery projects in Brazil are still few and concentrated mainly in large metropolitan regions.

Quantifying the energy and greenhouse gas (GHG) mitigation potential of sanitary landfills is essential to support investment decisions, public policy formulation, and the integration of waste-to-energy solutions into national energy planning. Although several studies have applied first-order decay models to estimate methane generation in landfills, there is still a lack of analyses that explicitly adjust model parameters to Brazilian conditions and compare the potential between cities of different sizes.

In this context, the present study evaluates methane generation, energy recovery, and carbon mitigation potential associated with MSW disposal in the two most populous municipalities in the state of Bahia, in northeastern Brazil, located about 100 km apart: Salvador, the state capital and one of the country's largest metropolises, and Feira de Santana, a medium-sized rapidly growing city and the second most populous in the state. Applying an approach based on the Landfill Gas Emissions Model - LandGEM [5] provides relevant technical insights into the role of landfill biomethane utilization in both large urban centers and medium-sized cities.

Biomethane

Biomethane is derived from the purification of biogas, the raw gas obtained from the biological decomposition of organic waste, according to Resolution 886/2022 of the National Agency of Petroleum, Natural Gas and Biofuels - ANP (Agência Nacional de Petróleo) [6]. Biomethane, therefore, has a high methane content in its composition and possesses properties that make it a substitute for natural gas in all its applications. Being renewable in origin, it is a substitute for fossil-derived Natural Gas (NG), hence also called Renewable Natural Gas (RNG).

The production of methane for energy purposes is mainly carried out from residual biomass from sanitary and agricultural landfills, which allow for continuous and sustainable production, contributing to clean energy generation and GHG emission mitigation [7].

A sanitary landfill is generally conceptualized as a giant biochemical reactor, where waste and water are the main inputs, while gas ("biogas") and leachate are the main outputs [8].

Methane production aimed at substituting NG requires biogas purification, a process that reduces concentrations of moisture, CO_2, and other substances, resulting in a methane-rich gas whose physical and chemical properties are like those of NG.

Biomethane can be marketed as compressed natural gas (CNG) or liquefied natural gas (LNG), and can be widely used in domestic, industrial, and vehicular sectors. The commercialization of biomethane is permitted for different actors, including state piped NG concessionaires and authorized distributors. This flexibility of use and commercialization, combined with its environmental advantages, makes biomethane a strategic fuel in the transition towards a more sustainable energy matrix and in strengthening the circular economy in Brazil [9].

Biomethane is a renewable fuel that contributes to GHG emission mitigation. Its production from organic waste prevents the release into the atmosphere of methane (CH_4), a gas with a global warming potential 28 times greater than that of carbon dioxide (CO_2) [10].

Energy Properties of Biomethane

In energy terms, 1 Nm^3 of biomethane is equivalent to 1 liter of diesel [11], with the advantage of being produced domestically from residual biomass and not being subject to the international price volatility of petroleum-derived fossil fuels traded in foreign currencies, such as diesel.

The Higher Heating Value (HHV) of biomethane is equivalent to the HHV of Natural Gas, ranging from [9.5 to 11.9\] kWh/m^3, according to ANP Resolution 866/2022 [6].

Considering that 1 ton of oil equivalent (toe) equals 11,630 kWh, the HHV of biomethane ranges from [0.0008 to 0.001] toe/m^3.

Mathematical Models for Estimating Methane Generation

The use of mathematical models allows for the assessment of the landfill's biomethane generation potential, the necessary adequate infrastructure, and the project's energy yield capacity. Modeling is an estimate where some parameters may be presumed and, in these cases, a simple mathematical model is preferable, one that uses few parameters concerning specific site conditions that can be reliable and easily obtained [12].

According to Gallego and colleagues [2] and Barros [13], several software tools exist for predicting biogas generation in a sanitary landfill, including:

- Biogas, Generation and Energy Use Landfills, version 1.0 [14].
- E-PLUS - Landfill Gas, version 1.0 (USEPA).
- IPCC - National Greenhouse Gas Inventories Programme (IPCC).
- LandGEM®, version 3.1 (USEPA).
- Scholl Canyon Model (World Bank).

Mathematical models have been developed to estimate landfill biomethane emissions based on waste disposal data, waste composition, moisture content, landfill cover material, and biogas collection [15]. A significant number of models have been developed and attracted the attention of many researchers in the field, including, but not limited to, the IPCC default model, the modified triangular method (MTM), the Dutch multiphase first-order model, AMPM, GASSFILL, the Scholl Canyon first-order model, the Rettenberger first-order model, the E-PLUS model, the German EPER zero-order model, the IPCC first-order model, the US EPA Landfill Biomethane Emissions Model (LandGEM). Among these, LandGEM is widely used to assess biomethane and other air pollutants from the decomposition of waste in sanitary landfills. The model was initially developed in 2005 by the US EPA based on a first-order decay (FOD) rate [16].

In the present work, we use the LandGEM landfill biogas emissions model to estimate the CH_4 generation potential.

Materials and Methods

<u>Methane Generation Model</u>

Methane generation from MSW disposal was estimated using a first-order decay (FOD) model consistent with LandGEM, developed by the United States Environmental Protection Agency – USEPA [17]. LandGEM is a Microsoft Excel spreadsheet (.xlsm) with enabled macros that utilizes Visual Basic for Applications (VBA) processes to function. The model assumes that methane generation follows an exponential first-order decay function, reflecting the progressive degradation of organic matter over time.

The annual methane generation rate is calculated by summing the contributions of waste deposited in previous years [5], according to Equation 1:

$$\boldsymbol{Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_{i,j}}} \qquad (1)$$

Where:

$\boldsymbol{Q_{CH4}}$ is the annual methane generation rate in the calculation year (m^3/year).

$\boldsymbol{i}$ is the 1-year time increment.

n is (year of calculation) - (initial year of waste acceptance).
j is the 0.1-year time increment.
k is the methane generation rate constant (yr^{-1}).
L_0 is the methane generation potential (m^3 CH$_4$/Mg MSW).
M$_i$ is the mass of waste accepted in the i-th year (Mg).
t_{ij} is the age of the ***j-th*** section of waste mass M_i accepted in the ***i-th*** year (decimal years, e.g., 3.2 years).

Parameter Adjustment to Brazilian Conditions

The default LandGEM parameters are predominantly based on waste composition and climatic conditions typical of the United States. To better represent Brazilian conditions, the model parameters were adjusted based on IPCC guidelines [18] and national waste composition data.

Methane Generation Rate Constant (*k*)

The Methane Generation Rate constant, *k*, determines the waste decomposition rate and the associated methane generation from the landfill. The value *k*, as used in the first-order decay rate equation, is in units of inverse years (i.e., 1/year or yr^{-1}). The higher the value of *k*, the faster methane generation occurs and the more quickly it will dissipate [19,20]. The rate constant can be translated into a half-life, as shown in Equation 2. In this case, the half-life represents the amount of time required for the remaining degradable carbon to decrease by 50% (i.e., step 1 = 50% of original carbon degraded, step 2 = 75%, step 3 = 87.5%, and so on).

$$t_{1/2} = \frac{\ln 2}{k} \quad (2)$$

Where:
$t_{1/2}$ is the half-life of biodegradable carbon and
$\ln 2$ is the natural logarithm of 2 (approximately 0.693).

The observed rate of decomposition has been linked to several factors, such as waste composition, moisture content of the waste mass, nutrient availability for microorganisms decomposing the waste, and temperature of the waste mass [21-23].

In LandGEM, *k* is linked to landfill moisture, considering both local precipitation and operational practices such as leachate recirculation or addition and solidification of wastewater liquids. Generally, areas receiving more precipitation are found to have higher methane generation rates [19,20,24].

Methane Generation Potential (L_0)

The Methane Generation Potential (L_0) depends solely on the composition of the waste deposited in the landfill. Anaerobically biodegradable components of waste, such as cellulose, hemicellulose, fats/lipids, and proteins, are broken down by microbes in a sequence that ultimately produces methane (CH$_4$) and carbon dioxide (CO$_2$) gases [5]. The higher the content of these components within the bulk waste mass, the higher the L_0 value. In the LandGEM first-order decay rate equation, L_0 is measured in metric units of cubic meters per megagram of waste [25].

Based on the LandGEM Manual, a decay constant $k = 0.05$ ***yr***$^{-1}$ was adopted for Feira de Santana and Salvador (Table 1).

The climate of Feira de Santana is tropical (As) and that of Salvador is tropical super-humid (Af), according to the Köppen-Geiger climate classification [26]. Both cities are classified as "non-arid" according to the LandGEM criterion.

The methane generation potential was set at $L_0 = 170$ ***m³ CH₄/Mg MSW***, a value compatible with the high organic matter content of Brazilian MSW, as reported by the Brazilian Association of Public Cleaning and Waste Companies - ABRELPE [27].

Table 1. Parameters and values for the NSPS applicability model.

Parameters	Unity	Non-Arid
k	year^{-1}	0.05
L_0	m^3 CH$_4$·/ Mg MSW	170
Methane Content	% biogas	50

Source: LandGEM Manual, Table 3 (p. 20).

In this context, "Arid" means geographical areas with 30-year average annual precipitation less than 25 inches, as measured at the nearest representative official meteorological site [25], which is not the case for either municipality studied.

Study Areas and Waste Data

In this study, we chose the two most populous cities in the state of Bahia, in the northeast region of the country, equipped with sanitary landfills and with biomethane utilization projects for energy purposes either implemented or under implementation: Salvador, the state capital and one of the most populous metropolises in the country, and Feira de Santana, a medium-sized rapidly growing city and the second most populous in the state.

For Salvador, whose project is already implemented and operating for thermoelectric generation from biogas and under implementation for direct biomethane utilization for energy purposes as renewable natural gas (RNG), MSW collection data were used for a 28-year period, with an average annual collection of 1 million Mg of waste. Despite having detailed data, an annual uniform distribution of collections was assumed to protect the source. Future projections of waste generation were made for the period from 2026 to 2062.

For Feira de Santana, whose project is under implementation for thermoelectric generation, the MSW collection data used was based on an approximate average of 310,000 Mg. Projections were made for the period from 2025 to 2075.

An annual growth rate of 5% for MSW deposition was assumed for both landfills, consistent with population growth, urban expansion, improvement in the population's purchasing power, and the increase in per capita waste generation observed in Brazilian cities.

In both cases, data were obtained from local waste collection service providers and are truthful, but we chose to protect the sources and details of the data that could identify them.

Estimation of Energy and Carbon Mitigation Potential

According to studies by Bueno and colleagues [30], the energy potential of the generated methane was estimated considering a lower heating value of 9.97 kWh/m³ CH_4 and an electrical conversion efficiency of 35%, representative of internal combustion engines widely used in landfill biogas energy utilization plants.

In general terms, the combustion of municipal waste produces fewer greenhouse gas emissions than other technologies, according to information collected by the United States Environmental Protection Agency - EPA (Table 2).

Table 2. Atmospheric emissions from different fuel sources in terms of carbon dioxide equivalent.

Fuel	CO_2 (kg/MWh)*
MSW	460.8
Coal	1,020.1
Oil	758.4
Natural Gas	514.8

* Emissions in kg of CO_2 equivalent per MWh of electricity produced. Source: EPA [28].

Results and Discussion

Methane Generation Profiles

The results indicate distinct methane generation profiles for the two municipalities, driven mainly by differences in the historical stock of disposed waste and future growth trajectories.

Salvador, the state capital and most populous city in Bahia, has approximately 2,500,000 inhabitants, while Feira de Santana, the second most populous city in the state, has about 660,000.00 inhabitants [29].

In Salvador, the large volume of accumulated waste results in sustained methane generation growth over the analyzed period, reaching maximum values above 1.7×10^8 m³ CH_4/year in 2062 and a total of 1.2×10^9 m³ CH_4 for the period 2013-2062. In Feira de Santana, methane generation grows more gradually due to the smaller population and corresponding lower initial MSW volume. However, the adopted growth rate leads to significant values in the long term, with peaks close to 2.5×10^8 m^3 CH_4/year in 2075 and a total of 5.9×10^9 m^3 CH_4 for the period 2013-2075.

These results highlight the cumulative effect of continuous waste generation growth in medium-sized cities and the potential to be harnessed for energy purposes.

Energy Recovery Potential

The estimate of maximum power generated at the sanitary landfill was calculated using Equation 3 [13,14,31]:

$$\boldsymbol{P = \eta \frac{PCI}{860,000} \varepsilon_C Q} \quad (\boldsymbol{MW}) \tag{3}$$

Where:
P is the available power (MW).
Q is the methane flow rate (Nm^3/h).
ε_C is the methane capture efficiency (50%).
η is the engine efficiency (35%).
Conversion factor: 1 kcal/h = (1/860,000) MW.
LHV = 8,500 kcal/Nm^3 CH_4.

Figure 1 presents the estimated annual methane generation rate for the Salvador (BA) Sanitary Landfill during its useful life, based on the expected MSW deposition over the years and using the LandGEM model with the kinetic parameters presented in Table 3. The methane generation peak occurs in 2062 with 1.7×10^8 m^3 CH_4/year, generating a Power of 33 MW (by Equation 3).

Figure 2 presents the estimated annual methane generation rate for the Feira de Santana (BA) Sanitary Landfill during its useful life, based on the expected MSW deposition over the years and using the LandGEM model with the kinetic parameters presented in Table 3. The methane generation peak occurs in 2075 with 2.5×10^8 m^3 CH_4/year, generating a Power of 49 MW (by Equation 3).

The estimated methane generation corresponds to a high energy recovery potential in both municipalities. In Salvador, the maximum methane flows result in an available electricity generation potential exceeding 40 MW, sufficient to supply 10,000 households with an average consumption of 150 kWh/month. In Feira de Santana, similar power levels are reached in the long term, demonstrating that medium-sized cities can also economically viabilize landfill biogas energy utilization projects.

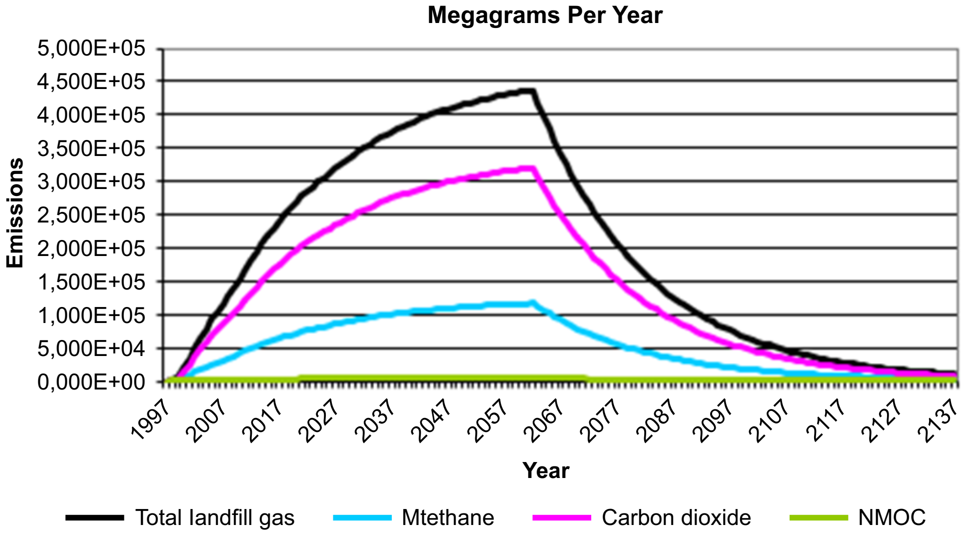
The results are consistent with international studies reporting electrical potentials of up to 70 MW for landfills in developing countries [32]. The high organic matter content of Brazilian MSW contributes to higher methane yields, partially compensating for the lower waste volumes in intermediate-sized cities.

The results demonstrate that landfill biogas utilization can and should be considered a central component of integrated waste management and energy planning strategies. In the Brazilian context, the implementation of biogas recovery systems can simultaneously reduce GHG emissions and generate renewable energy.

Conclusions

This study applied an adjusted LandGEM-based approach to evaluate methane generation and the energy recovery potential associated with municipal solid waste (MSW) disposal in the two most populous municipalities in the state of Bahia, in northeastern Brazil, located about 100 km apart: Salvador and Feira de Santana. The results demonstrate that both Salvador, the capital and most populous city in the state of Bahia, and Feira de Santana, the second most populous city in the state, exhibit high potential for the utilization of bioenergy from sanitary landfills. In Salvador, opportunities are immediate and large-scale for bioenergy generation, due to the significant historical waste stock, with a methane generation peak in 2062 of 1.7×10^8 m^3 CH_4/year, generating a Power of 33 MW, with energy utilization via a thermoelectric plant already operating since 2011

Figure 1. Estimate of the methane generation rate at the Salvador (BA) Sanitary Landfill.



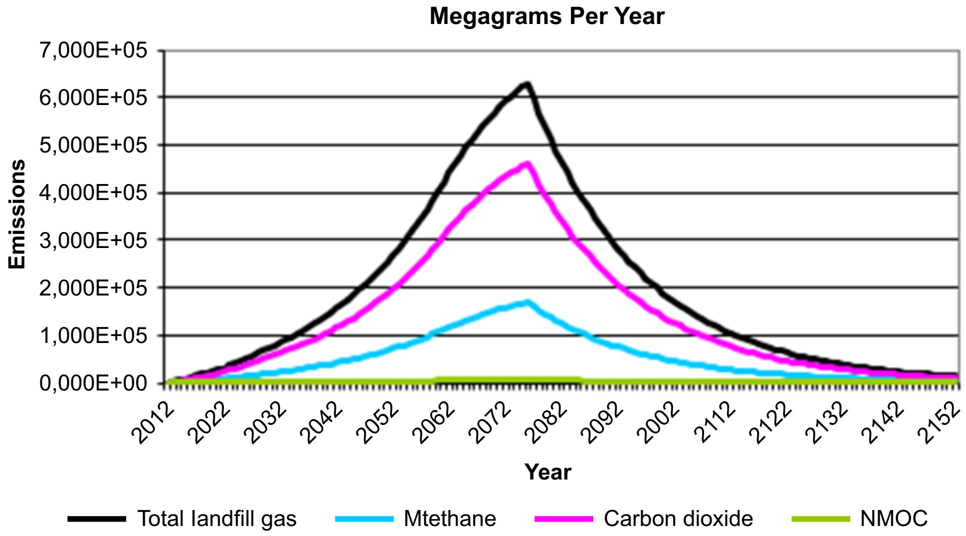
Source: Prepared by the authors based on data entered into LandGEM.

Table 3. Input Data - LandGEM.

Input Review		
LANDFILL CHARACTERISTICS	**Salvador**	**Feira de Santana**
Landfill Open Year	1997	2012
Landfill Closure Year (with 80-year limit)	2062	2075
Actual Closure Year (without limit)	2062	2075
Have Model Calculate Closure Year?	Yes	Yes
Waste Design Capacity [megagrams]		
MODEL PARAMETERS		
Methane Generation Rate, ***k*** [year^{-1}]	0.050	
Potential Methane Generation Capacity, ***Lo*** [m^3/Mg]	170	
NMOC Concentration [ppmv as hexane]	4,000	
Methane Content [% by volume]	50	
GASES / POLLUTANTS SELECTED		
Gas / Pollutant #1	Total landfill gas	
Gas / Pollutant #2	Methane	
Gas / Pollutant #3	Carbon dioxide	
Gas / Pollutant #4	NMOC	

Source: Prepared by the authors based on data entered into LandGEM.

Figure 2. Estimate of the methane generation rate at the Feira de Santana (BA) Sanitary Landfill.



Source: Prepared by the authors based on data entered into LandGEM.

and a biomethane utilization project as RNG in the implementation phase. In Feira de Santana, whose energy utilization project via a thermoelectric plant is still under implementation, the estimated potential reaches comparable levels of biogas generation in the long term due to the continuous growth of waste generation. The methane generation peak occurs in 2075 with 2.5×10^8 m^3 CH_4/year, generating a Power of 49 MW. Combined, the generation of the two units totals 82 MW, half the capacity of the Pedra do Cavalo HPP, located in the Feira de Santana region, with significantly lower installation and management costs, in addition to using waste as raw material, contributing to the circular economy, elimination of environmental liabilities, and GHG emissions. The results reinforce the relevance of integrating waste-to-energy into Brazilian energy transition strategies.

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