Mitigation potential of super-emitting landfills in Brazil

Estimating mitigation potential and associated abatement costs

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CARBON LIMITS

Executive Summary

This study assessed methane emissions and mitigation opportunities at 66 landfill sites in Brazil identified as super-emitters through Carbon Mapper satellite observations from September 19th, 2024, to July 7th, 2026. Based on annualised Carbon Mapper observations processed using Monte Carlo uncertainty propagation, the assessed sites emit an estimated 642 kilotons of methane per year ($ktCH_4$/year), equivalent to approximately 29% of methane emissions from Brazil's solid waste disposal sector reported by Brazil Greenhouse Gas Emissions and Removals Estimating System (SEEG).

The analysis estimates that approximately 456 $ktCH_4$/year of these emissions could be mitigated through improved landfill gas collection and utilisation, representing around 71% of observed emissions. Most of this potential (266 $ktCH_4$/year) is associated with sites that already have gas collection systems in place, indicating that optimisation and expansion of existing infrastructure may be as important as installing new systems.

The results show that a relatively small number of sites account for a large share of the total mitigation potential. The top 10 emitting sites account for 37% of the total mitigation potential for the 66 super-emitters, while the top 20 emitting sites account for 57%. These sites also have the lowest abatement costs, making them attractive candidates for near-term action.

Reducing methane emissions through interventions at the landfills appears to be a relatively low-cost mitigation opportunity in Brazil. Of the 66 assessed sites, 57 have abatement costs below 10 USD per ton of carbon dioxide equivalent (USD/tCO_2e) and represent 95% of the total mitigation potential. The weighted average abatement cost is approximately 5 USD/tCO2e for the top 10 emitting sites and 7 USD/tCO2e for the top 20. The highest emitting landfills therefore offer the most cost-effective opportunities and could be prioritised for near-term action. For sites with higher abatement costs, carbon markets, climate finance and revenues from landfill gas utilisation could help improve project economics and unlock additional emission reductions.

Overall, the findings indicate that substantial methane reductions can be achieved through targeted interventions at a limited number of large super-emitting landfills. Prioritising investment in these sites through the installation of new gas collection systems and the optimisation and expansion of existing systems, supported by measurement-based monitoring, could provide a rapid and cost-effective pathway for reducing methane emissions from Brazil's waste sector.

Table of Contents

Executive Summary 2
Table of Contents 3
Abbreviations 4
1 Introduction 6
1.1 Context for study 6
1.2 Landfill methane emissions in Brazil 6
1.3 Scope and objectives of the study 7
2 Data collection and characterisation of assessed sites 8
2.1 Landfill characteristics 8
2.2 Carbon Mapper dataset 11
2.3 Default parameters and assumptions 12
3 Analytical approach 13
3.1 Estimation of methane emissions 13
3.1.1 Carbon Mapper dataset uncertainty propagation 13
3.1.2 FOD model calculations 14
3.2 Estimation of mitigation potential 15
3.2.1 Methane capture efficiency 15
3.2.2 Mitigation potential 16
3.3 Estimation of abatement costs 17
3.3.1 Selection of the most appropriate mitigation pathway 17
3.3.2 Estimated project cost parameters 18
3.3.3 Costs associated with the gas collection system 18
4 Results 20
4.1 Satellite-observed methane emissions 20
4.2 FOD-modelled emissions 22
4.3 Mitigation potential 24
4.4 Abatement costs 26
5 Discussion 29
5.1 Implications for methane mitigation in Brazil 29
5.2 Comparison of modelled FOD emissions and observed Carbon Mapper emissions 30
5.3 Impact of alternative landfill management practices 30
5.4 Co-benefits of landfill gas collection 31
6 Conclusions 32
7 References 33

Abbreviations

Abbreviation	Definition
CAPEX	Capital expenditure
CATF	Clean Air Task Force
CCEE	Electricity Trading Chamber (Câmara de Comercialização de Energia Elétrica)
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CR	Capture rate
CSLL	Social Contribution on Net Profit
EPA	United States Environmental Protection Agency
FOD	First Order Decay
IBGE	Instituto Brasileiro de Geografia e Estatística
IPCC	Intergovernmental Panel on Climate Change
IRPJ	Corporate Income Tax
IRR	Internal rate of return
ITMO	Internationally Transferred Mitigation Outcome
kt	Kilotonne
kg	Kilogram
km^2	Square kilometre
LFG	Landfill gas
LFGcost	Landfill Gas Energy Cost model
L0	Methane generation potential
MCF	Methane Correction Factor
MSW	Municipal Solid Waste
Mt	Megatonne
MWh	Megawatt-hour
NIR	National Inventory Report
NPV	Net Present Value
O&M	Operation and maintenance
OPEX	Operating expenditure
OX	Oxidation factor
R$	Brazilian real
SEEG	System for Estimating Greenhouse Gas Emissions and Removals

SINISA	National Sanitation Information System
tCH_4	Tonne of methane
tCO_2e	Tonne of carbon dioxide equivalent
USD	United States Dollar

1 Introduction

1.1 Context for study

Methane emissions from solid waste disposal sites are a significant contributor to global greenhouse gas emissions and represent an important opportunity for near-term climate mitigation. Recent advances in satellite and remote sensing technologies have improved the ability to detect and quantify methane emissions from individual landfills and dumpsites, enabling the identification of facilities with particularly high emissions and complementing existing landfill emission models.

In Brazil, satellite observations have identified numerous super-emitting waste disposal sites, providing new insights into methane emissions across the sector. This report builds on methane observations provided by Carbon Mapper and applies established methodologies to assess emissions, mitigation opportunities, and the costs of implementing landfill methane mitigation measures at these facilities. The analysis provides an indication of the potential emissions reductions and climate benefits that could be achieved through targeted action at high-emitting sites.

1.2 Landfill methane emissions in Brazil

Brazil generated and collected approximately 78 million tonnes of municipal solid waste (MSW) in 2023[1], with collection services covering 91% of the population. Organic waste accounted for approximately 43% of the waste stream, providing substantial potential for methane generation when disposed of in landfills and dumpsites.[2]

Landfilling remains the dominant waste management pathway in Brazil. In 2023, 74.4% of collected waste was disposed of in sanitary landfills, while 15.3% was disposed of in open dumps and 10.3% in controlled landfills. Brazil reported 688 sanitary landfills, 317 controlled landfills, and 1,606 open dumps in operation in 2023. While sanitary landfills received approximately 50.8 million tonnes of waste, open dumps and controlled landfills together received more than 17 million tonnes, demonstrating that these disposal practices continue to account for a substantial share of collected waste despite ongoing efforts to modernise the sector.[3]

The waste sector emitted approximately 91 $MtCO_2e$ (million tons of carbon dioxide equivalent) in 2022, with methane accounting for almost all waste-sector greenhouse gas emissions. Solid waste disposal sites, including landfills and dumpsites, contribute to just over half of waste-sector methane emissions (53 $MtCO_2e$). Of these emissions, 82.5% (44.1 $MtCO_2e$) originated from managed waste disposal sites, while the remaining 17.5% (9.4 $MtCO_2e$) came from uncategorized disposal sites (see Figure 1).[4]

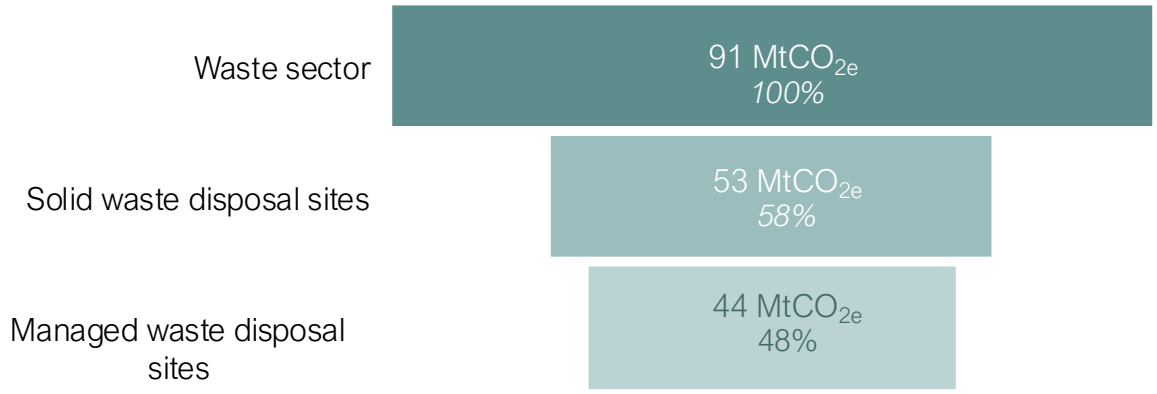
[1] Ministério das Cidades (2025). *Relatório dos Serviços de Limpeza Urbana e Manejo de Resíduos Sólidos – SINISA 2024 (ano de referência 2023)*. Available at: https://www.gov.br/cidades/pt-br/acesso-a-informacao/acoes-e-programas/saneamento/sinisa/resultados-sinisa (Accessed in September 2026)

[2] ABREMA (2024). *Panorama dos Resíduos Sólidos no Brasil 2024*. Available at: https://www.abrema.org.br/panorama/ (Accessed in September 2026)

[3] Ministério das Cidades (2025). *Relatório dos Serviços de Limpeza Urbana e Manejo de Resíduos Sólidos – SINISA 2024 (ano de referência 2023)*. Available at: https://www.gov.br/cidades/pt-br/acesso-a-informacao/acoes-e-programas/saneamento/sinisa/resultados-sinisa (Accessed in September 2026)

[4] Government of Brazil (2024). *Brazil National Inventory Report 2024*. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/relatorios-bienais-de-transparencia-btrs/relatorios_slogo/bra_nir_2024_eng_slogo.pdf (Accessed September 8th, 2026)

Figure 1. Breakdown of waste sector greenhouse gas emissions, from total emissions to managed waste disposal sites.



Source: Brazil National Inventory Report (2024)[5]

Methane recovery from landfill gas systems plays an important role in mitigating these emissions. In 2024, approximately 581.2 $ktCH_4$ (kilotons of methane) were recovered from 54 sanitary landfills.[6]**Error! Bookmark not defined.** According to the System for Estimating Greenhouse Gas Emissions and Removals (SEEG), landfill gas recovery avoided emissions equivalent to approximately 25% of the methane that would otherwise have been released from solid waste disposal sites.

Data availability has improved significantly through the National Sanitation Information System (SINISA) national reporting system. However, data quality challenges remain because municipal reporting is largely self-declared, many municipalities lack robust waste information systems, and only a limited share of municipalities have conducted recent waste composition studies.[6]

1.3 Scope and objectives of the study

This study assesses the methane mitigation potential of waste disposal sites in Brazil identified as methane super-emitters through satellite observations provided by Carbon Mapper. The assessment covers 66 landfills and dumpsites and supports the Brazil Satellite Super-Emitter Initiative by quantifying emissions, mitigation opportunities, and the costs associated with methane reduction measures at these sites.

The objectives of the study are to:

- Estimate annual methane emissions for each identified super-emitting site and assess their contribution to methane emissions from Brazil's waste sector.
- Identify mitigation measures and landfill gas management pathways applicable to the assessed sites and estimate the emission reductions achievable through their implementation.
- Estimate the costs associated with implementing mitigation measures, including capital investment requirements and operating costs.
- Assess the broader benefits of methane mitigation, including potential revenues from landfill gas recovery and qualitative environmental and public health co-benefits.

[5] Government of Brazil (2024). *Brazil National Inventory Report 2024*. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/relatorios-bienais-de-transparencia-btrs/relatorios_slogo/bra_nir_2024_eng_slogo.pdf (Accessed September 8th, 2026)

[6] Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG), Observatório do Clima (2025). *Análise das emissões de gases de efeito estufa e suas implicações para as metas climáticas do Brasil (1970–2024)*. Available at: https://seeg.eco.br (Accessed October 6th, 2026).

- Provide a qualitative assessment of alternative landfill management practices beyond landfill gas collection systems and their potential influence on methane emissions, landfill conditions, and gas recovery performance.

To achieve these objectives, the study combines satellite-derived methane observations, landfill-specific information collected through the project, first-order decay modelling, and cost assessments based on the United States Environmental Protection Agency (U.S. EPA) Landfill Gas Energy Cost (LFGcost) model adapted using Brazil-specific assumptions and financial parameters.

The study provides preliminary estimates of methane mitigation potential and costs across the assessed sites, intended to support prioritisation of methane mitigation opportunities and inform future implementation efforts. The results should not be considered a substitute for detailed site-specific engineering, feasibility, or investment studies.

2 Data collection and characterisation of assessed sites

Carbon Mapper provided methane observations for the identified super-emitting waste disposal sites in Brazil. This dataset formed the scope of the work for this study. The Carbon Mapper data was supplemented with data collected from Instituto PNRS (the Brazilian Institute for Solid Waste).

Data were gathered from three primary sources: (i) landfill-specific information collected through data collection templates and publicly available sources, (ii) methane emission observations provided by Carbon Mapper, and (iii) default parameters derived from established international methodologies and relevant literature.

2.1 Landfill characteristics

Landfill-specific information gathered included landfill location, ownership, waste quantities, population served, landfill age, operating characteristics, landfill classification, and the presence and performance of landfill gas collection systems where available. Additional information regarding landfill gas utilisation, methane recovery volumes, and operational practices was also compiled where possible.

The assessed landfill sites represent a diverse range of facility sizes, ownership structures, and operating conditions. The sites are distributed across all major regions of the country and include both publicly and privately operated landfills. While the portfolio includes several small and medium-sized municipal facilities, it is dominated by larger regional and metropolitan landfills, with one-third of sites serving populations exceeding one million people and half serving between 250,000 and one million people.

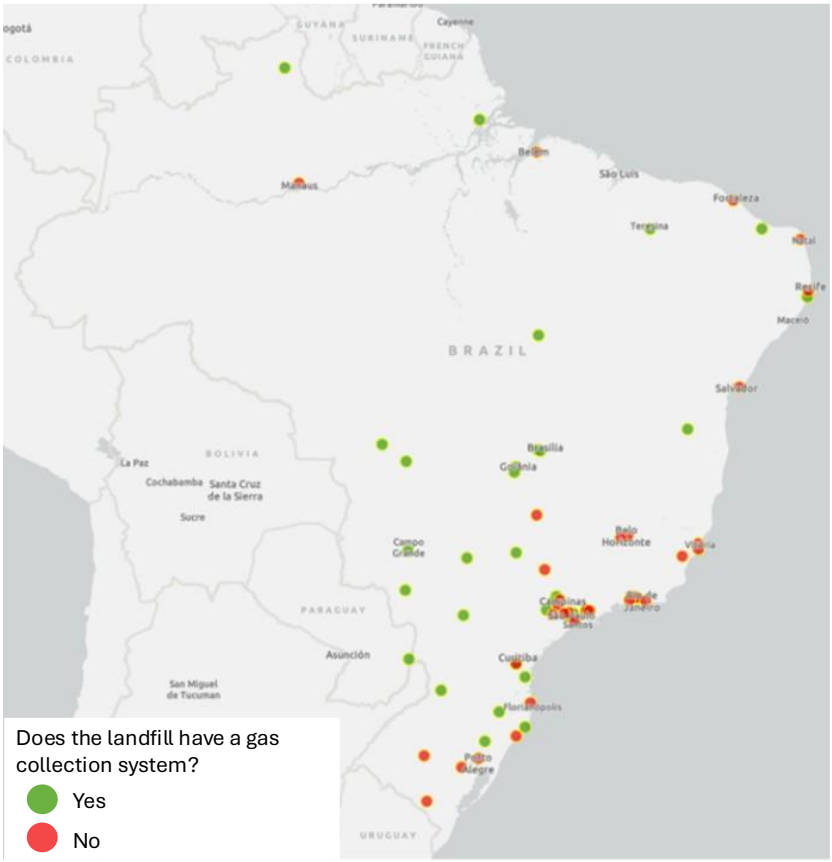
Most of the sites are classified as managed anaerobic landfills (91%), although a small number of unmanaged disposal sites were also identified. Landfill gas management practices vary significantly across the portfolio. Approximately 50% of sites have landfill gas collection systems, while the remaining 50% do not. A larger share of privately owned landfills has implemented gas collection systems (69% of private landfills) than publicly owned landfills (22% of public landfills). Several of the largest facilities, including CTR Seropédica, Aterro Sanitário de Caieiras, Aterro Sanitário Sítio São João and Novo Aterro Sanitário - ASMOC II have implemented landfill gas recovery projects for energy generation, flaring, or biomethane production.

The main characteristics for the sites are summarized in Table 1 below.

Table 1 - Characteristics of assessed landfill sites

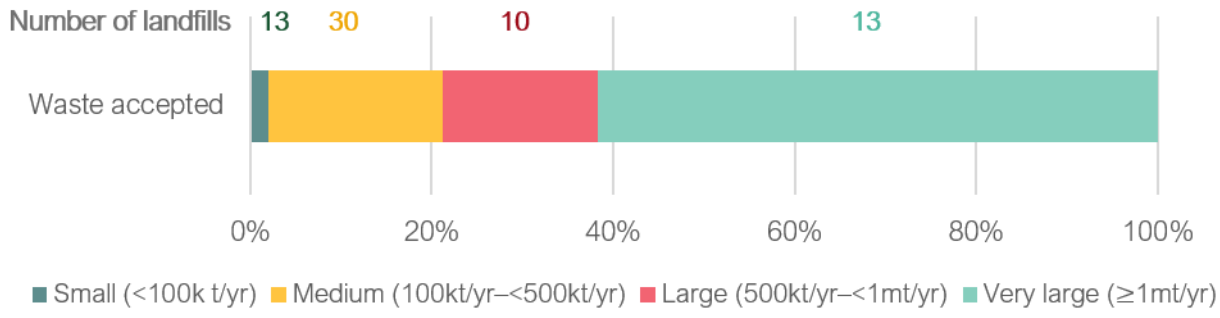
Category	Characteristic		Number of sites	Share of sites
Overall	Total sites assessed		66	100%
Gas collection system	With a gas collection system		33	50%
	Without a gas collection system		33	50%
Size by population served	Small, fewer than 250,000 people		10	15%
	Medium, 250,000 to 1 million people		33	50%
	Large, more than 1 million people		23	35%
Size by annual waste disposal	Small, less than 250,000 tonnes/year		31	47%
	Medium, 250,000 to 1 million tonnes/year		22	33%
	Large, more than 1 million tonnes/year		13	20%
Ownership classification	Private		39	59%
	Public		27	41%
Landfill management classification	Managed anaerobic landfill		60	91%
	Unmanaged landfill or dumpsite		5	8%
	Other or unknown		1	2%
Ownership classification and gas collection system	**Private**	With a gas collection system	27	41%
		Without a gas collection system	12	18%
	Public	With a gas collection system	6	9%
		Without a gas collection system	21	32%

Figure 2 - Map of assessed landfill sites



Collectively, the assessed facilities receive approximately 40 million tonnes of waste annually, equivalent to a substantial share of the total waste disposed of in sanitary landfills in Brazil. The 13 largest facilities, each receiving more than 1 million tonnes of waste annually, collectively account for approximately 24.5 million tonnes of annual waste disposal, representing approximately 61.5% of the total waste accepted across the assessed portfolio. In contrast, the 13 small (<100k tonnes / year) and 30 medium-sized (100-500k tonnes / year) landfills account for just over one-fifth of total disposed waste.

Figure 3 - Percentage of total waste accepted for assessed sites



The analysed sites also show substantial variation in physical characteristics. The combined landfill surface area is approximately 30 km^2, with individual landfill footprints ranging from less than 0.3 square kilometre (km^2) to approximately 9 km^2. Landfill area, however, was found to be only moderately correlated with annual waste acceptance.

The portfolio is characterised by the strong presence of several large private waste management companies. Following consolidation of operator names, Orizon and SOLVI operate ten and nine of the assessed sites, respectively, representing the largest management groups within the dataset.

2.2 Carbon Mapper dataset

For each landfill, the dataset included information on the number of methane plume detections, the number of observation days, source persistence, coordinates, estimated methane emission rates, and associated uncertainty values from September 19th, 2024, to July 7th, 2026.

A landfill may have one or more methane plumes attributed to it in the Carbon Mapper dataset. Multiple plumes may be detected during a single observation day and therefore do not necessarily represent independent emission events. To characterize the frequency of emissions, Carbon Mapper uses the number of detection days (days with at least one plume detected) and the number of observation days (days on which the landfill was observed under suitable conditions). These metrics are used to calculate the source persistence, which reflects how frequently emissions are detected over time.

For each landfill, Carbon Mapper provided the information summarized in Table 2 below.

Table 2. Information provided in the Carbon Mapper dataset.

Field[7]	Description
Source ID	Unique identifier assigned to each landfill.
Coordinates	Latitude and longitude of the landfill location.
Plume count	Total number of plumes detected and attributed to the landfill.
Detection date count	Number of days on which one or more plumes were detected at the landfill.
Observation date count	Number of days on which the landfill was observed under suitable conditions, regardless of whether methane emissions were detected.
Persistence	Ratio detection days (*Detection date count*) to days (*Observation date count*) for the source, representing the intermittency (frequency with which emissions are detected). *For example, if a landfill is observed on 10 different days and plumes are detected on 2 of those days, the persistence is 20%.*[8] For the present dataset, persistence values are provided directly by Carbon Mapper.
Emission rate (kg/hr)	Average methane emissions from a source over time. Daily average emission rates are first calculated from all plume observations, and the average of these daily values is then multiplied by the source persistence.

[7] Carbon Mapper (2025). Product Guide: Data Definition & Specification. Available at: https://carbonmapper.org/articles/product-guide (Accessed in September 2026)

[8] Carbon Mapper (2026). *Frequently Asked Questions (FAQs).* Available at: https://carbonmapper.org/about/faq (Accessed in September 2026)

Field[7]	Description
	This accounts for both variability in emission rates when the source is active and periods of inactivity. *For example, if the daily average emission rate is 225 kg/h and the source persistence is 20%, the resulting source emission rate would be 45 kg/h. The reported source emission rate therefore reflects the long-term average emissions of the source rather than the emission rate of an individual plume.*[9]
Emission uncertainty	Uncertainty associated with the reported source emission rate.

2.3 Default parameters and assumptions

Several parameters required for the analysis could not be derived directly from site-specific information and were therefore obtained from established modelling approaches, national datasets, and literature sources. These include assumptions related to waste composition, methane generation rates, landfill management categories, landfill gas collection efficiencies, technology applicability thresholds, and cost assumptions.

Methane generation calculations were based on the Intergovernmental Panel on Climate Change (IPCC) First Order Decay (FOD) methodology. State-level waste composition data were derived from Table 8.7 in Brazil's National Inventory Report[10], while climate-specific methane generation parameters were selected based on regional climatic conditions. Default values were used for the two climate zones for the degradable organic carbon (DOC) content and fraction decomposed (DOCf) for each waste type, as well as the waste specific methane generation rate constants (k). The model also assumed a methane fraction (F) of 0.5, a six-month delay before methane generation, and default methane correction factors (MCFs) according to landfill management type.[11] No methane oxidation was assumed in the FOD calculations.

For the abatement cost assessment, the U.S. EPA LFGcost model was adapted using Brazil-specific financial assumptions, including local interest rates, inflation rates, tax rates, and electricity prices. These inputs were used to estimate the capital investment requirements, operating costs, energy revenues, and financial performance of landfill gas mitigation projects.

For the country-specific financial parameters, the values presented in Table 3 were used.

Table 3 - Brazil-specific financial parameters

Parameter	Value	Comment/Source
Interest rate	14%	Selic interest rate as of August 2026[12]

[9] Carbon Mapper (2026). *Frequently Asked Questions (FAQs).* Available at: https://carbonmapper.org/about/faq (Accessed in September 2026)

[10] Government of Brazil (2024). *Brazil National Inventory Report 2024*. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/relatorios-bienais-de-transparencia-btrs/relatorios_slogo/bra_nir_2024_eng_slogo.pdf (Accessed September 8th, 2026)

[11] Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste, Chapter 3: Solid Waste Disposal*. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf (Accessed in September 2026)

[12] Banco central do Brazil (2026). *Selic interest rate*. Available at: https://www.bcb.gov.br/en/monetarypolicy/selicrate (Accessed in September 2026)

Parameter	Value	Comment/Source
General inflation rate	4.44%	Instituto Brasileiro de Geografia e Estatística (IBGE) 12 months until July 2026[13]
Equipment inflation rate	4.44%	Assumed to follow the inflation rate
Marginal tax rate	34%	Combination of Corporate Income Tax (IRPJ) and Social Contribution on Net Profit (CSLL) levies[14]
Electricity price	240.43 Brazilian real (R$)/Megawatt-hour (MWh)	Average for July 2025-July 2026[15]
Electricity price	46.67 USD/MWh	Converted using the DNB currency converter as of 13-08-2026 at 0.19 Brazilian Real/USD[16]
Annual product price escalation rate	4.44%	Assumed to follow the inflation rate
Operation and maintenance (O&M) for Collection & Flaring systems	50% of default input EPA model	Adjustment to reflect lower labour costs in Brazil compared with the United States.

3 Analytical approach

3.1 Estimation of methane emissions

3.1.1 Carbon Mapper dataset uncertainty propagation

To account for uncertainty in the Carbon Mapper source emission rates, a Monte Carlo uncertainty propagation approach was applied to the Carbon Mapper source emission rates using RStudio. This approach is based on Carbon Limits (2024)[17] and Chen et al (2022).[18]

For each source/landfill, 50,000 iterations were performed. During each iteration, an emission rate was randomly sampled from a normal distribution with a mean equal to the Carbon Mapper source emission rate and a standard deviation derived from the reported uncertainty assuming a 95% confidence interval. This

[13] Instituto Brasileiro de Geografia e Estatística (IBGE). *Dashboard of indicators.* Available at: https://www.ibge.gov.br/en/indicators.html (Accessed in September 2026)

[14] Brazil tax brief (2026). Corporate Tax in Brazil: The Complete Guide for Foreign Companies (2026). Available at: https://braziltaxbrief.com/posts/corporate-tax-brazil-complete-guide/ (Accessed in September 2026)

[15] Electricity Trading Chamber (Câmara de Comercialização de Energia Elétrica) (CCEE). *Panel de preços.* Available at: https://www.ccee.org.br/en/precos/painel-precos (Accessed in September 2026)

[16] DNB (2026). *Currency converter.* Available at: https://www.dnb.no/en/markets/fx-and-ir/currency-converter (Accessed in September 2026)

[17] Carbon Limits (2024). *Methane Super Emitters – Low Cost, High Impact: Satellite Insights on Global Methane Super-Emitters.* Available at: https://www.carbonlimits.no/projects/methane-super-emitters-kizd1 (Accessed in July 2026)

[18] Chen et al. (2022). *Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey.* Available at: https://pubs.acs.org/doi/10.1021/acs.est.1c06458 (Accessed in July 2026)

approach generates a synthetic distribution of possible emission rates consistent with the reported measurement uncertainty.

The resulting distribution was used to estimate minimum, mean, and maximum hourly emission rates for each landfill. The mean of the 50,000 simulated values was retained as the representative source emission rate used in the analysis, while the minimum and maximum values provided an indication of the uncertainty range. This process was repeated for each landfill in the dataset.

Unlike Carbon Limits (2024), the Bernoulli sampling step was not replicated because Carbon Mapper's source emission rate already incorporates source persistence through the ratio of detection days to observation days. The Monte Carlo analysis therefore propagated only the uncertainty associated with the reported source emission rate.

Hourly emission rates were finally converted to annual methane emissions by multiplying the Carbon Mapper source emission rate by the number of hours in a year:

$$\text{Annual emissions (t } CH_4\text{/year)} = \frac{\text{Source emission rate (kg/h)} \times 8{,}760}{1{,}000}$$

This calculation assumed that the Carbon Mapper source emission rate, which already incorporates source persistence, is representative of average emissions throughout the year.

Limitations and uncertainties

The mitigation potential estimates are based on methane emissions observed by Carbon Mapper rather than the total methane generation potential of each landfill. Consequently, the analysis estimates the portion of observed emissions that could potentially be mitigated through improved landfill gas management, rather than the maximum technically recoverable methane.

Several factors contribute to uncertainty in the observed emissions, including:

- Carbon Mapper's detection threshold, which limits the detection of smaller, diffuse, or intermittent emission sources
- Variability in satellite coverage, observation frequency, and meteorological conditions
- The possibility that large emissions occurred outside the observation periods
- Uncertainties in the annualisation of observed methane plumes

As a result, the estimated mitigation potential may underestimate the total technically achievable emission reductions at sites where actual methane generation exceeds observed emissions.

3.1.2 FOD model calculations

In addition to the Carbon Mapper data, the First Order Decay (FOD) method[19] was used to estimate methane generation potential at the assessed landfills. The calculations were based on the best available information on waste quantities, waste composition, landfill age, and operational characteristics collected throughout the project. Where site-specific information was unavailable, appropriate default parameters were applied.

[19] Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste, Chapter 3: Solid Waste Disposal*. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf (Accessed in September 2026)

State-specific waste composition data were derived from Table 8.7 of Brazil's 2024 National Inventory Report (NIR).[20] The methane generation constant "k" was assigned based on the climate zones as presented in the Bluegreenatlas.[21] Temperate regions were classified as "Wet Temperate" and Tropical regions as "Moist and wet Tropical" in the FOD model, reflecting mean annual precipitation levels that generally exceed the model's 1000 mm threshold for wet conditions.

For landfill sites with existing landfill gas collection systems that can provide operational data, an additional FOD-based scenario incorporating landfill gas capture volumes is calculated. Sites for which no information on the performance of their Landfill Gas (LFG) system could be provided, literature-based default values will be applied. These calculations then ultimately yield emission numbers for:

- FOD-estimated methane generation without gas collection
- FOD-estimated methane emissions with gas collection

3.2 Estimation of mitigation potential

3.2.1 Methane capture efficiency

A methane capture efficiency of 85% was assumed to represent the performance of a well-designed and well-operated landfill gas collection system, which is consistent with default values provided by the U.S. EPA's Greenhouse Gas Reporting Program[22] and the LFGcost model.[23]

The selected value should not be interpreted as the typical performance achieved by all landfills. Collection efficiency depends on numerous site-specific factors, including landfill design, cover quality, well spacing, operational practices, waste age, and maintenance of the gas collection network. A recent review of landfill gas collection efficiency literature found substantial variability among sites and concluded that no single collection efficiency value is universally applicable. For landfills with final cover systems, the range of reported collection efficiencies was approximately **72-93%**[24], while lower efficiencies were generally observed for sites with intermediate cover or less developed collection systems.

Similarly, Barlaz et al. (2009)[25] reported temporally averaged collection efficiencies ranging from approximately **55% to 91%**, depending on landfill characteristics, climate conditions, cover type and the extent of gas collection coverage.

Given these findings, 85% is considered an ambitious but achievable target representative of good industry practice rather than average landfill performance. It is therefore used in this study as an assumption to estimate the methane reduction potential associated with improved landfill gas management.

Factors influencing methane capture efficiency

[20] Government of Brazil (2024). *Brazil National Inventory Report 2024*. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/relatorios-bienais-de-transparencia-btrs/relatorios_slogo/bra_nir_2024_eng_slogo.pdf (Accessed in September 2026)

[21] Blue Green Atlas. (n.d.). *The climate of Brazil*. Available at: https://bluegreenatlas.com/climate/brazil_climate.html (Accessed in September 2026)

[22] U.S. Environmental Protection Agency (EPA) (2025). *Table HH-3 to Subpart HH of Part 98 – Landfill Gas Collection Efficiencies*. Available at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98/subpart-HH/appendix-Table%20HH-3%20to%20Subpart%20HH%20of%20Part%2098 (Accessed in September 2026)

[23] U.S. Environmental Protection Agency (EPA) (2023). *Landfill Gas Energy Cost Model (LFGcost-Web) User's Manual, Version 3.6.* Available at: https://www.epa.gov/system/files/documents/2023-09/lfgcost_web_v3.6_usersmanual_sep2023.pdf (Accessed in September 2026)

[24] Environmental Research & Education Foundation (EREF) (2025). *Critical Analysis of Literature on Landfill Gas Collection Efficiency – Executive Summary*. Available at: https://erefdn.org/wp-content/uploads/2025/03/Landfill-Gas-Collection-Efficiency-Executive-Summary.pdf (Accessed in September 2026)

[25] Barlaz, M.A., Chanton, J.P. and Green, R.B. (2009). *Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance*. Available at: https://www.tandfonline.com/doi/pdf/10.3155/1047-3289.59.12.1399 (Accessed in September 2026)

Achieving high methane capture rates requires more than simply installing a landfill gas collection system. Literature highlights several operational and design practices that significantly improve collection performance:

- Early installation and expansion of gas collection infrastructure during landfill operation
- Minimisation of active working faces and exposed waste areas
- Rapid installation of intermediate and final cover systems
- Use of low-permeability cover materials
- Proper maintenance and balancing of extraction wells
- Continuous monitoring and optimisation of collection system performance[26,27]

Limitations and uncertainties

The analysis assumes a target landfill gas collection efficiency of 85% for all sites and mitigation pathways. This assumption is intended to provide a consistent basis for estimating mitigation potential from currently observed emissions. Actual collection efficiency may vary substantially among sites, and the 85% assumption should be interpreted as an ambitious good-practice target rather than typical current performance.

Collection efficiencies can vary depending on factors including landfill design, waste characteristics, cover conditions, the configuration of the gas collection network, operational practices, and site age. Consequently, the estimated mitigation potential should be considered indicative and subject to uncertainty associated with the assumed target collection efficiency.

3.2.2 Mitigation potential

The mitigation potential was estimated based on observed methane emissions derived from Carbon Mapper data, regardless of whether a landfill gas collection system is already in place.

For all landfills, it was assumed that an improved or newly implemented gas collection system could capture 85%[28] of the observed methane emissions. The mitigation potential was therefore calculated as:

$$Mitigation\ Potential = MAX(0; 0.85 \times (CH_4_collected + CH_4_observed) - CH_4_collected)$$

The CH_4_observed methane emissions were based on the Carbon Mapper observations and the CH_4_collected emissions were based on the data provided through the data collection process by Instituto PNRS.

Note: As the FOD estimates were higher than the observed emissions at some sites and lower at others, these were not used directly to calculate mitigation potential. Instead, they served as an independent reference for assessing the plausibility of observed emissions and supporting interpretation of the results.

Limitations and uncertainties

Mitigation potential is assumed to depend solely on improvements in landfill gas collection. The analysis therefore implicitly assumes that all captured methane is successfully destroyed or utilised and does not account for differences in methane destruction or utilisation efficiencies between flares, engines, turbines, upgrading systems, or other end-use technologies.

[26] Lair, A., Mansuy, M., Romand, C., Oberti, O., Pradels, C., Barina, G., Denoun, T., Venturini, M. and Trommsdorff, C. (2024). *Enhancing landfill efficiency to drive greenhouse gas reduction: A comprehensive study on best practices and policy recommendations*. Available at: https://journals.sagepub.com/doi/pdf/10.1177/0734242X241270951 (Accessed in September 2026)

[27] U.S. Environmental Protection Agency (EPA) (2020). *LFG Energy Project Development Handbook: Chapter 7 – Best Practices for Landfill Gas Collection System Design and Installation*. Available at: https://www.epa.gov/sites/default/files/2020-03/documents/pdh_chapter7.pdf (Accessed in September 2026)

[28] EPA model default values.

In practice, methane destruction efficiencies vary across technologies and operating conditions. The estimated mitigation potential should therefore be interpreted as an estimate of methane capture potential, rather than a detailed assessment of net greenhouse gas reductions for a specific utilisation pathway.

Furthermore, the analysis only quantifies direct methane emission reductions resulting from improved landfill gas management. Additional climate benefits associated with the use of recovered landfill gas, such as the displacement of fossil fuel-based electricity, natural gas, or other fuels, are not included.

The analysis also assumes that the current waste composition and organic waste input remain unchanged. Consequently, alternative mitigation approaches that reduce methane generation directly or indirectly, such as organic waste diversion, improved cover practices, biocovers, semi-aerobic operation, or active aeration, are not quantified. The estimated mitigation potential therefore reflects improvements in landfill gas collection under the existing waste management conditions rather than the full range of potential landfill methane mitigation measures. The reported mitigation potential should therefore be considered conservative.

3.3 Estimation of abatement costs

3.3.1 Selection of the most appropriate mitigation pathway

Although the EPA model can evaluate a wide range of technologies, not all options are appropriate for every landfill. Therefore, Carbon Limits (together with the Clean Air Task Force (CATF) and Carbon Mapper) identified a preferred mitigation pathway for each site based on its technical characteristics, including:

- Existing LFG systems
- Landfill size and associated estimated landfill gas generation potential

The selection framework for the technology to implement is presented in Table 4:

Table 4 - LFG technology selection matrix

Landfill Profile	Recommended Technology	Key Rationale
Small landfill (<175 kg CH_4/hr)	Small-scale electricity generation (small reciprocating engines)	• Lower gas flow rate best suited for smaller engines
Medium landfill (175-750 kg CH_4/hr)	Electricity generation (standard reciprocating engine)	• Too low value for a gas turbine, but high enough for standard engine
Large landfill (>750 kg CH_4/hr)	Electricity generation (gas turbine)	• Enough LFG flow to support a gas turbine

The gas flow rate requirements were based on the landfill flow characteristics recommended for landfill gas collection and utilisation technologies as described in the LFG energy project development handbook[29] and the LFG cost user's manual from the EPA.[30] The original values in cubic feet of landfill gas were converted

[29] U.S. Environmental Protection Agency. (2024). *LFG energy project development handbook*. Landfill Methane Outreach Program. Available at: https://www.epa.gov/lmop/landfill-gas-energy-project-development-handbook (Accessed in September 2026)

[30] U.S. Environmental Protection Agency. (2023). *LFGcost-Web user's manual (Version 3.6)*. Landfill Methane Outreach Program. Available at: https://www.epa.gov/lmop/lfgcost-web-landfill-gas-energy-cost-model (Accessed in September 2026)

and rounded to cubic meter and finally kg of methane using a 50% average methane content of landfill gas. The methane flow rate for each landfill was based on the emissions data from Carbon Mapper.

For sites with existing gas collection systems and data on gas collection volumes, these numbers were added up with the emission observations from Carbon Mapper to give the total gas flow rate that was used for the selection of the appropriate technology.

3.3.2 Estimated project cost parameters

For each landfill, the preferred mitigation pathway (selected in the previous step) was evaluated using the US EPA model that estimates:

- Capital investment requirements
  - LFG energy project capital costs with Brazil-specific variables where available (and applicable)
  - Total installed capital costs
- Annual operating and maintenance (O&M) costs associated with running the LFG collection system
- Energy production and recovery
  - Electricity generation or energy production potential
  - Energy recovery revenues
- Cost effectiveness of methane mitigation
  - Methane abatement cost (USD/t CH_4 avoided)
  - Greenhouse gas abatement cost (USD/tCO_{2e} avoided)
- Financial performance indicators
  - Net Present Value (NPV)
  - Internal Rate of Return (IRR)
  - Years to breakeven/payback

Capital expenditure (CAPEX), annual operating costs (OPEX), net present value (NPV) and abatement cost (USD/tCO_2e) were used as the key financial indicators. The abatement costs were calculated by dividing the NPV of the mitigation measure by the cumulative emission reductions achieved over the lifetime of the LFG system. A system lifetime of 15 years was assumed, consistent with the default assumption in the U.S. EPA model.

3.3.3 Costs associated with the gas collection system

Scenario 1: No existing gas collection system

For landfills without an existing gas collection system, CAPEX and OPEX associated with landfill gas collection were estimated directly using the EPA LFGcost model.

The model assumes that a new collection system, including wells, piping, and associated infrastructure, must be installed.

Scenario 2: Existing gas collection system

For landfills with an existing gas collection system, the mitigation scenario assumed improvement and expansion of the current system rather than installation of a new collection system across the entire landfill.

The following parameters are used:

- $Q_{captured}$ = methane currently captured by the landfill gas collection system;
- $Q_{observed}$ = methane emissions observed by Carbon Mapper;
- $CR_{observed}$ = estimated current observed capture rate (CR) = $\frac{Q_{captured}}{Q_{captured} + Q_{observed}}$
- CR_{target} = target capture rate (85%)

The additional improvement required to reach the target capture rate was represented by the scaling factor calculated as: $MAX(0, \frac{CR_{target} - CR_{observed}}{CR_{target}})$

This factor was applied to the total landfill area to approximate the additional area requiring effective LFG collection coverage. As collection system costs in the EPA model are scaled according to landfill area, this approach allowed the costs of additional wells and associated collection infrastructure to be estimated without treating the landfill as if an entirely new system were required.

Costs associated with electricity generation were treated separately. The EPA model estimates the required engine or turbine capacity and associated costs based on the gas flow available for utilisation. As the gas flow input in the mitigation scenario represented only the **additional** methane captured as a result of improving the existing system, the corresponding electricity generation costs were automatically scaled to the additional gas volume.

This approach therefore provides a simplified method for estimating the incremental costs of improving an existing LFG system. The area-based scaling factor should be interpreted as a cost-scaling proxy, rather than a direct estimate of the physical area currently without collection infrastructure. In practice, achieving the target capture rate may involve a combination of expanding collection coverage, installing or replacing extraction wells, improving wellfield balancing and maintenance, upgrading blowers and gathering infrastructure, and other operational improvements.

Limitations and uncertainties

The cost estimates presented in this study should be interpreted as screening-level indicators for comparing projects rather than as definitive investment appraisals. The assessment is based on the EPA LFGcost model and does not fully capture site-specific engineering conditions, landfill design, operational practices, regulatory requirements, or local market conditions. Actual project costs may therefore differ substantially from the values presented and should be confirmed through site-specific engineering and feasibility studies.

Several assumptions have a significant influence on the results. Local construction, equipment, labour, and operating costs may differ from those assumed in the model, while landfill-specific characteristics such as waste depth, cover conditions, gas well density, and existing infrastructure can substantially affect investment requirements. For landfills with existing gas collection systems, CAPEX and OPEX estimates are based on the estimated mitigation potential remaining at the specific site. This mitigation potential is used to estimate the remaining landfill area for which well infrastructure would need to be installed. Uncertainties around the actual landfill waste area and the absence of information regarding the current area coverage of landfill gas infrastructure add to the uncertainty of this cost estimate. In practice, some sites may require varying levels of investments to upgrade the gas collection and utilisation system to reach the maximum gas capture potential.

The results also highlight the sensitivity of estimated abatement costs to site-specific input data. In particular, unusually large landfill gas collection system requirements relative to mitigation potential may reflect uncertainties in landfill surface area data or other site-specific assumptions. These inputs should therefore be verified when assessing individual projects in greater detail.

Finally, the economic results are highly sensitive to assumptions regarding electricity prices, discount rates, inflation, and project lifetimes. The analysis uses a discount rate of 9%, which has a significant impact on project NPVs. Access to concessional finance, climate funds, or other forms of lower-cost financing could substantially improve project economics.

4 Results

4.1 Satellite-observed methane emissions

Processed and annualised Carbon Mapper observations indicate average methane emissions of 642 $ktCH_4$/year across the analysed landfills. This corresponds to approximately 29% of the methane emissions reported for Brazil's Solid Waste sector in 2024 (2,253 $ktCH_4$/year according to SEEG).[31] The observed emissions are not expected to correspond to the reported emissions. Differences between the figures can be explained by the scope and characteristics of the Carbon Mapper dataset, which covers only large emission plumes under favourable observation conditions and doesn't represent all diffuse and intermittent landfill emissions for the whole country.

Of the total observed emissions, 420 $ktCH_4$/year (65%) originate from landfills where a landfill gas collection system is reported to be in place[32], whereas 223 $ktCH_4$/year (35%) originate from landfills without gas collection systems. Notably, landfills equipped with gas collection systems represent 50% of the observed landfill sites, yet account for more than three-fifths of the detected emissions.

These results suggest that the presence of a gas collection system does not necessarily result in low methane emissions. Significant emissions may persist due to incomplete collection coverage, gas leaks through landfill covers, inefficient wellfield operation, inadequate maintenance, delayed expansion of the collection network as the landfill grows, or methane escaping through the landfill working face.

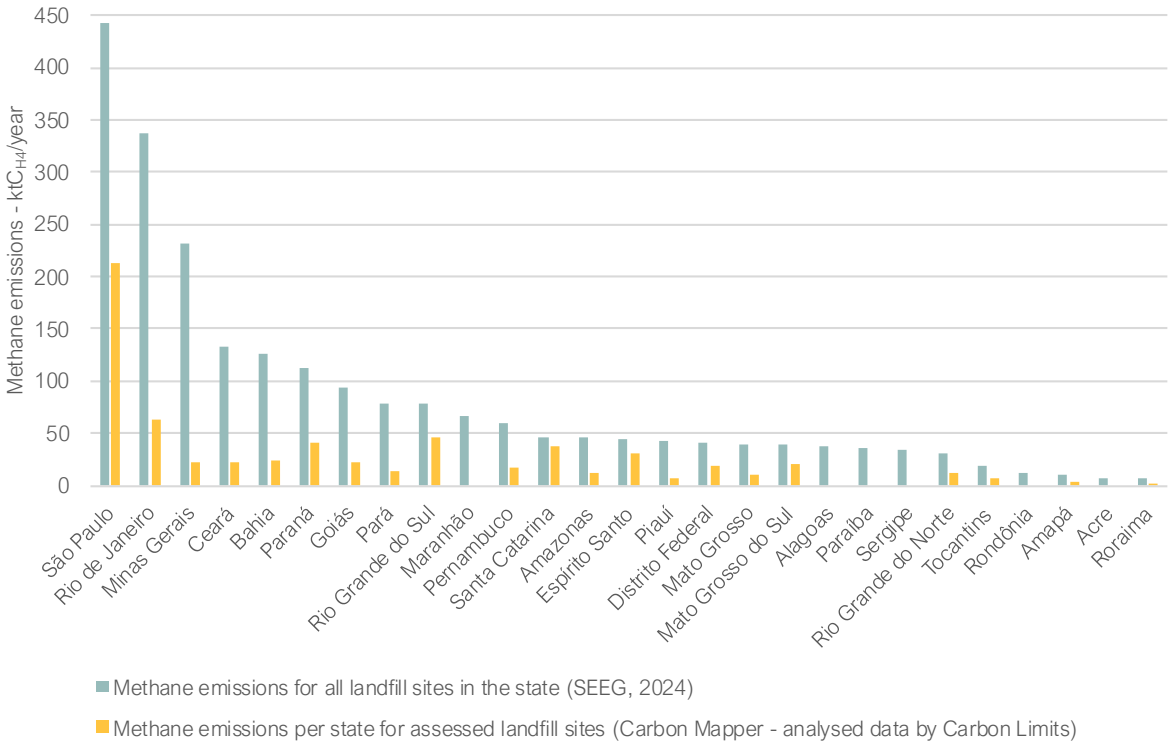
The observed emission distribution should not be interpreted as evidence that all existing systems are ineffective. Rather, the satellite observations can be used to effectively identify key mitigation opportunities for landfills with- and without gas collection systems. The observed emission distribution indicates that substantial methane mitigation opportunities may remain at many landfills despite the presence of gas collection infrastructure, highlighting the importance of system optimisation, maintenance, expansion, and verification through independent measurements.

Both Carbon Mapper and SEEG datasets show a strong concentration of emissions in a small number of states (see Figure 4). This suggests that targeted mitigation efforts at a limited number of landfills, particularly in São Paulo (22 observed landfills), Rio de Janeiro (5 observed landfills) and other states with high observed emissions, could deliver significant methane reductions and should be prioritized for follow-up investigation and assessment of gas collection system performance.

[31] SEEG (2024). *Waste Sector - Final Disposal methane emissions*. Available at: https://plataforma.seeg.eco.br/?yearRange%5B0%5D=2024&yearRange%5B1%5D=2024&sector%5B0%5D=586&category%5B0%5D=1175&emissionType%5B0%5D=1&gas=1&groupBy=State&rankBy=State&filtersTab=filters&statisticsTab=historical (Accessed in September 2026)

[32] Data collected from government

Figure 4. State-wide reported versus observed methane emissions per state



Source: Carbon Limits analysis based on Carbon Mapper observations and SEEG data

The ratio between Carbon Mapper observations and SEEG-reported methane emissions varies considerably across Brazilian states (see Figure 5). Several factors may explain these differences, including:

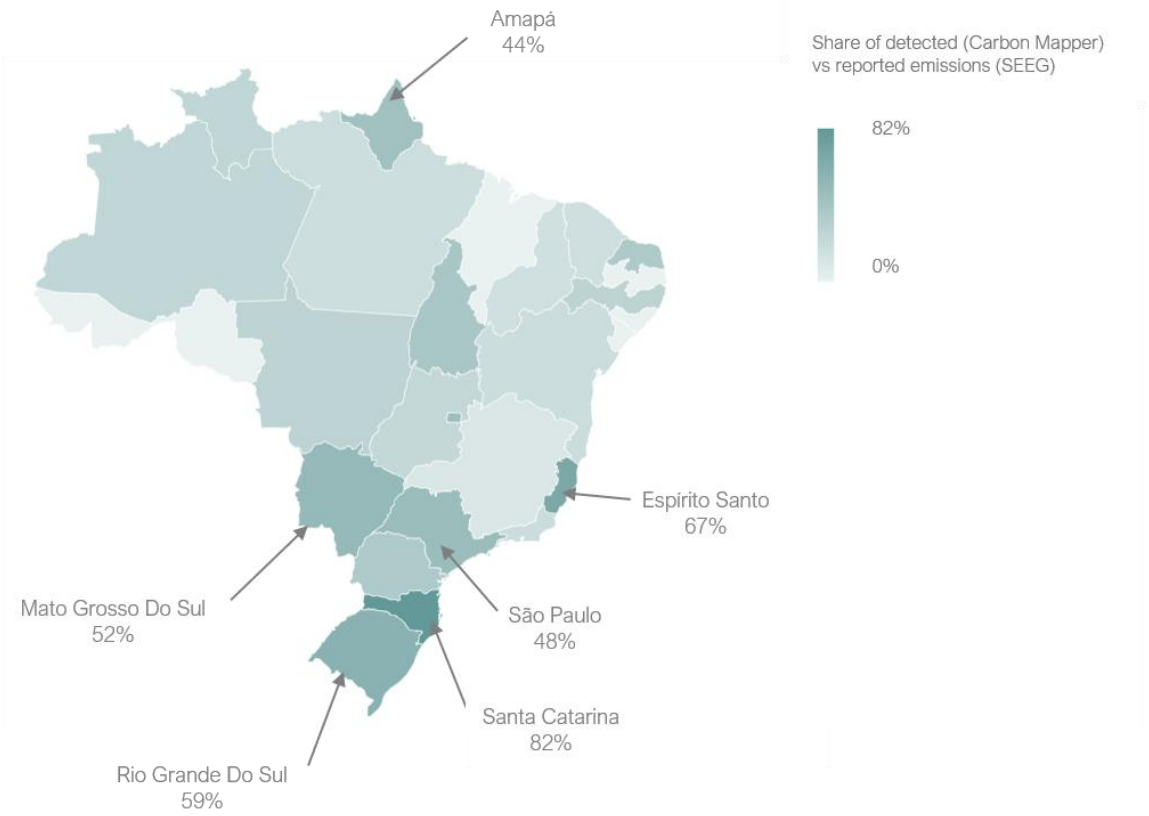
- Variations in landfill infrastructures and management practices
- Differences in the design, operation and performance of landfill gas collection systems
- Uneven spatial and temporal coverage of satellite observation across states
- Emissions occurring below Carbon Mapper's detection threshold.
- Variations in environmental and meteorological conditions at the time of satellite observation

In some states, particularly Santa Catarina (6 observed landfills) and Rio Grande do Sul (5 observed landfills), Carbon Mapper observations represent a relatively large share of SEEG-reported emissions. This may indicate that a small number of high-emitting landfills account for a substantial share of state-level emissions, although differences in observation coverage and conditions may also contribute. Further site-level investigation would be required to determine the factors underlying these results.

In contrast, several states, including Acre, Roraima, and Amapá, show very low or no observed emissions despite non-zero methane emissions reported in the SEEG inventory. This does not necessarily indicate low or no landfill methane emissions, as emissions may not have been observed during satellite overpasses due to reasons described above and may generally have been too small or dispersed to be detected.

Figure 5 compares annualised methane emissions derived from Carbon Mapper observations with SEEG estimates of methane emissions from final waste disposal at the state level. The percentages represent the ratio of Carbon Mapper-derived emissions to SEEG-estimated emissions and should not be interpreted as the proportion of total emissions detected by Carbon Mapper. They can rather be used to help identify regions where emissions are more concentrated for a small number of facilities. For example, in the state of Rio Grande Do Sul, methane emissions detected by Carbon Mapper account for 59% of the total emissions estimated and reported by SEEG for that same state.

Figure 5. Carbon Mapper-derived emissions as a share of SEEG-estimated landfill methane emissions



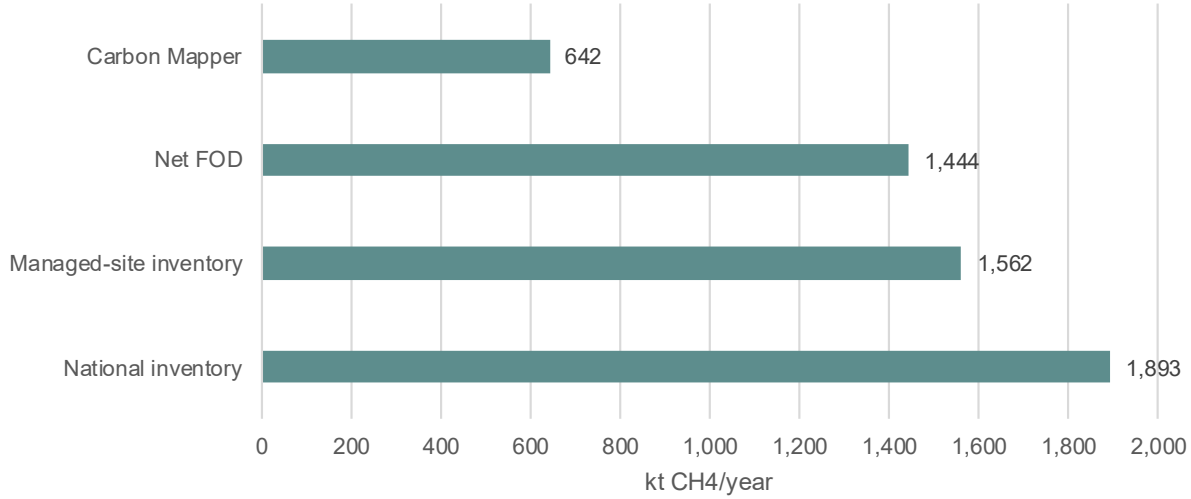
Source: Carbon Limits analysis based on Carbon Mapper observations

4.2 FOD-modelled emissions

The First Order Decay (FOD) model was applied to all 66 assessed waste disposal sites using landfill-specific information on waste quantities, landfill age, waste composition (state-level), climatic conditions, and landfill management characteristics. Where information on landfill gas recovery was available, reported methane recovery volumes were incorporated into the calculations to estimate net methane emissions under current operating conditions.

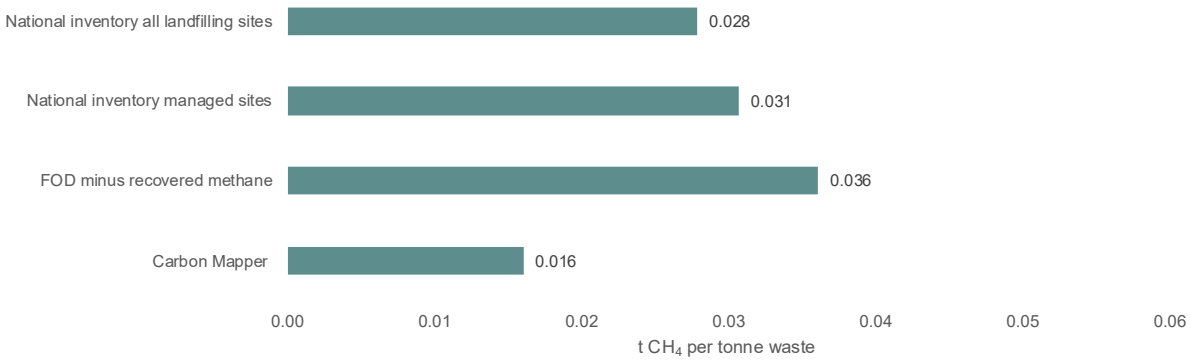
Using this approach, the assessed landfills were estimated to emit approximately 1,444 $ktCH_4$/year in total in 2025. By comparison, annualised Carbon Mapper observations indicate methane emissions of approximately 642 $ktCH_4$/year, equivalent to approximately 44% of the emissions estimated by the FOD model. Figure 6 shows the total methane emission estimates for four sources: the Carbon Mapper dataset for the 66 assessed facilities, the FOD model developed for this study adjusted for landfill gas collection data obtained through the landfill information survey (Net FOD) for the 66 facilities, Brazil-wide managed landfill emissions reported in the National Inventory Report (NIR), and total landfill emissions for the whole country reported in the NIR.

Figure 6 - Total emission estimates as reported in the national inventory (NIR), FOD calculations, and Carbon Mapper observations



To understand the emission intensity associated with landfilled waste, total methane emissions were normalised by the annual quantity of waste disposed. This metric provides an indication of the implied methane generation and emission rates underlying the national inventory, the landfill-specific FOD calculations, and the Carbon Mapper observations. Based on the combined information from the National Inventory Report (NIR), SEEG data, and the assessed landfill portfolio, the resulting methane intensities are presented in Figure 9.

Figure 7 – Methane intensity indicator per tonne waste deposited



The comparison of the methane intensities demonstrates that Carbon Mapper observations are on average lower than both the national inventory and the recovery-adjusted FOD estimates. The Carbon Mapper observations correspond to an average of approximately 0.016 tCH_4/t waste, compared with 0.031 tCH_4/t waste for the managed-landfill component of the national inventory and 0.036 tCH_4/t waste for the recovery-adjusted FOD calculations. The recovery-adjusted FOD estimates are broadly agreeing with the national estimates being approximately 18% higher than the managed-site inventory estimate, while the Carbon Mapper observations are approximately 48% lower than the managed-site inventory estimate and 51% lower than the recovery-adjusted FOD calculations. The relatively close agreement between the FOD-based estimates and the national inventory is also consistent with their methodological basis, as Brazil's NIR also applies the FOD approach to estimate methane emissions from solid waste disposal.

These comparisons should be interpreted with caution, as the satellite observations and FOD-based estimates represent fundamentally different approaches to characterising landfill emissions. Carbon Mapper

observations detect methane plumes from sufficiently large, concentrated point sources under suitable observation conditions, whereas FOD models estimate total methane generation and emissions over time. In addition, converting discrete satellite observations into annualised emission estimates introduces uncertainty because landfill emissions can vary over time and satellite sampling is intermittent. Reconciling point-source satellite observations with bottom-up landfill models and deriving representative annual averages from satellite measurements is still a topic that is being studied.[33] The aggregate comparison presented here should therefore be understood as a comparison of complementary emission estimates rather than a direct validation of either approach.

Overall, the comparison shows that the FOD calculations produce substantially higher aggregate methane emissions than the Carbon Mapper observations. Considering both sources of information therefore provides a more complete basis for interpreting methane emissions across the assessed landfills.

4.3 Mitigation potential

A substantial share of the methane emissions observed across the assessed landfills could potentially be avoided through improved landfill gas (LFG) management. Based on the methodology described in Section 3.2, approximately 456 $ktCH_4$/year, corresponding to 71% of the 642 $ktCH_4$/year annualised emissions derived from Carbon Mapper observations and 20% of reported solid waste emissions for Brazil in 2024[34], could be mitigated through (i) the implementation of new gas collection systems at sites where none currently exist (189 $ktCH_4$/year) and (ii) performance improvements at landfills already equipped with gas collection infrastructure (266 $ktCH_4$/year). As highlighted in Figure 8, for landfills without existing gas collection systems, the estimated mitigation potential corresponds to 85% of observed emissions from that group, reflecting the assumed target capture efficiency. For sites with existing systems, the corresponding mitigation potential is approximately 63%, after accounting for methane already being collected.

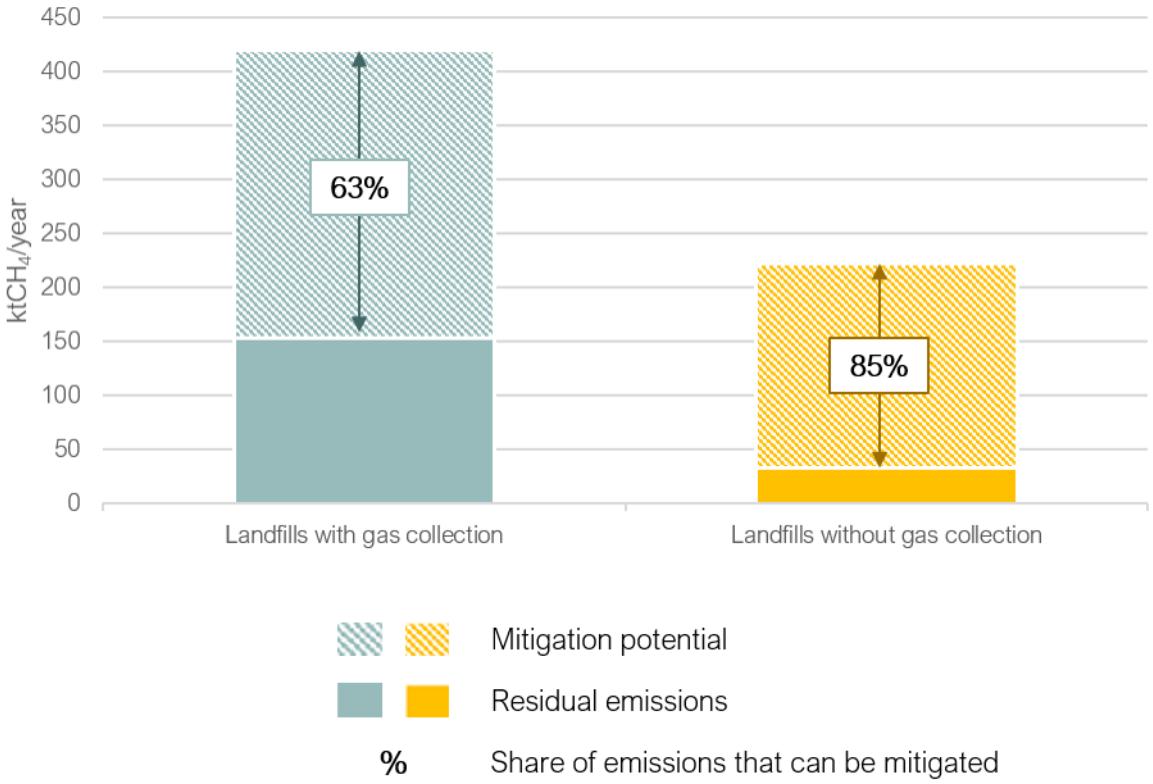
The larger mitigation potential associated with sites that already have LFG collection reflects the high observed emissions at several of these landfills. This indicates that mitigation strategies should consider both improvements to existing systems and the installation of new collection infrastructure.

For landfills without gas collection systems, mitigation could be achieved through the installation of active gas extraction systems combined with appropriate methane destruction or utilisation technologies.

[33] Scarpelli, T., Cusworth, D., Kim, J., O'Neill, K., Duren, R., and Howell, K.: Using point source imaging satellite observations to guide landfill methane model improvements at the national and sub-national scale, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-7927, https://doi.org/10.5194/egusphere-egu26-7927, 2026

[34] SEEG (2024). *Waste Sector - Final Disposal methane emissions*. Available at: https://plataforma.seeg.eco.br/?yearRange%5B0%5D=2024&yearRange%5B1%5D=2024&sector%5B0%5D=586&category%5B0%5D=1175&emissionType%5B0%5D=1&gas=1&groupBy=State&rankBy=State&filtersTab=filters&statisticsTab=historical (Accessed in September 2026)

Figure 8. Mitigation potential and residual emissions of landfills with and without gas collection systems in place.



Source: Carbon Limits analysis based on Carbon Mapper observations

Residual emissions represent the portion of emissions remaining after the identified mitigation opportunities have been implemented.

The estimated mitigation potential varies between Brazilian states, ranging from approximately 45% to 85% of observed emissions. These differences are primarily driven by:

- The proportion of landfills already equipped with gas collection systems
- The amount of methane currently being captured and destroyed or utilised
- The performance of existing collection systems relative to the assumed target collection efficiency of 85%
- Site-specific factors such as landfill size.

It should be noted that the estimated mitigation potential only considers direct methane emission reductions resulting from increased methane capture and destruction or utilisation. Additional climate benefits may be realised where captured methane is used to generate energy or replace fossil fuels. In such cases, the recovered landfill gas can displace electricity generated from fossil fuel sources or substitute natural gas and other fossil fuels in industrial, commercial, or transport applications. These avoided fossil fuel emissions are not included in the mitigation potential presented here, meaning that the overall climate benefit of landfill gas recovery projects could be higher than the direct methane reduction estimates reported in this assessment.

Finally, the estimated mitigation potential should be considered an indicative upper-bound estimate based on observed emissions and assumed collection performance targets. Site-level technical assessments would be required to confirm the feasibility, cost-effectiveness, and achievable emission reductions for individual landfills.

4.4 Abatement costs

The abatement cost analysis indicates that significant landfill methane reductions can be achieved at relatively low cost, particularly at larger landfills with high methane generation potential. Across the assessed landfills, larger sites generally have lower abatement costs than smaller sites, reflecting economies of scale in LFG collection and utilisation.

Based on the technology screening approach described in Section 3.3.1, 37 sites were assigned to gas turbine projects, 25 sites to standard reciprocating engine projects, and 4 sites to small engine projects. Gas turbine projects account for approximately 345 $ktCH_4$/year of mitigation potential, representing around three-quarters of the total, and have the lowest median abatement cost of approximately 6.59 USD/tCO_2e. Standard engine projects account for approximately 107 $ktCH_4$/year with a median abatement cost of approximately 8.22 USD/tCO_2e, whereas small engine projects account for 3.7 $ktCH_4$/year and have a substantially higher median cost of approximately 17.35 USD/tCO_2e. These results are summarized in Table 5.

Table 5 - Results abatement costs per project type

Technology	Projects	Total CAPEX ($m)	Total Mitigation Potential (kt CH_4/yr)	Median cost ($/$tCO_2e$)	Median CAPEX ($m)
Small Engine	4	14.8	3.7	17.35	3.57
Standard Engine	25	252.8	106.8	8.22	11.03
Standard Turbine	37	811.6	345.0	6.59	19.52

The results indicate that larger projects tend to have lower abatement costs. Large metropolitan landfills such as Aterro Sanitário Municipal de Guarulhos, CTDR Mauá, Caieiras, Estre Ambiental - CGR Iguaçu, and Sítio São João combine high methane recovery potential with gas volumes sufficient to support larger energy recovery technologies, resulting in comparatively low costs per tonne of emissions avoided. Several of these sites have abatement costs below 5 USD/tCO_2e, placing them among the lowest-cost methane mitigation opportunities identified in the analysis.

Landfills with existing gas collection infrastructure also generally show lower abatement costs than sites where new systems would need to be installed. Existing-system sites account for approximately 266 $ktCH_4$/year of mitigation potential and have a median abatement cost of approximately 6.48 USD/tCO_2e. In comparison, sites without gas collection systems account for approximately 189 $ktCH_4$/year of mitigation potential and have a median abatement cost of approximately 8.52 USD/tCO_2e. These results are summarized in Table 6.

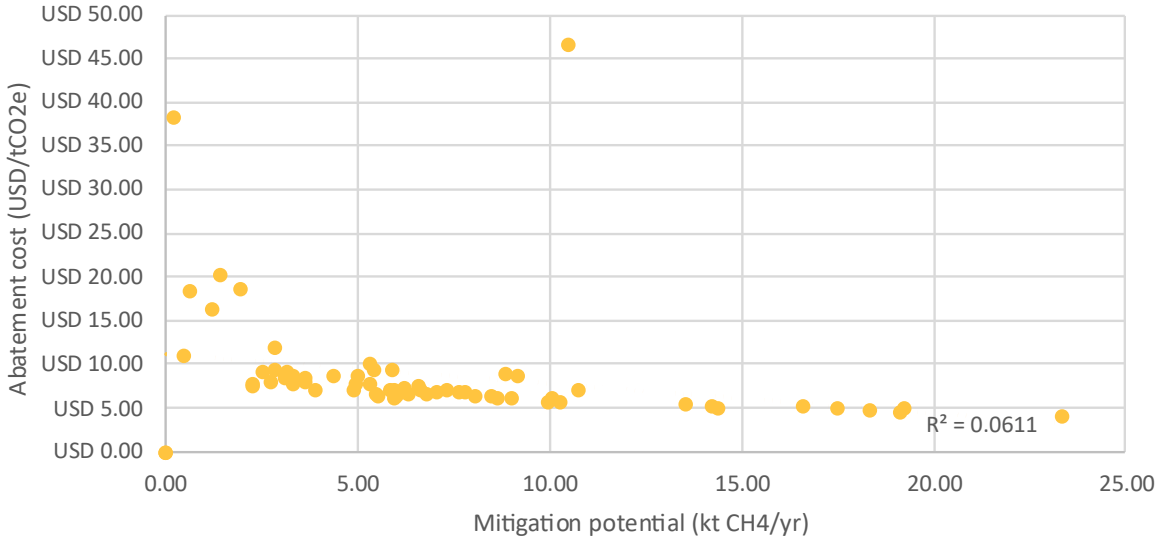
Table 6 - Abatement costs for landfills with/without existing gas collection systems

Existing gas collection	Projects	CAPEX ($m)	Mitigation (kt CH_4/yr)	Median cost ($/$tCO_2e$)
Yes	33	645.2	266.4	6.48
No	33	434.0	189.2	8.52

Figure 9 shows that the abatement costs are influenced by both mitigation potential and the scale of the required collection infrastructure. While many projects cluster below 10 USD/tCO_2e, a small number of sites have substantially higher costs, reaching close to 50 USD/tCO_2e. These higher costs are primarily

associated with sites that combine relatively low mitigation potential with large collection-system footprints, resulting in high investment requirements relative to the volume of emissions that can be mitigated.

Figure 9 - Scatter plot of abatement costs and mitigation potential per landfill



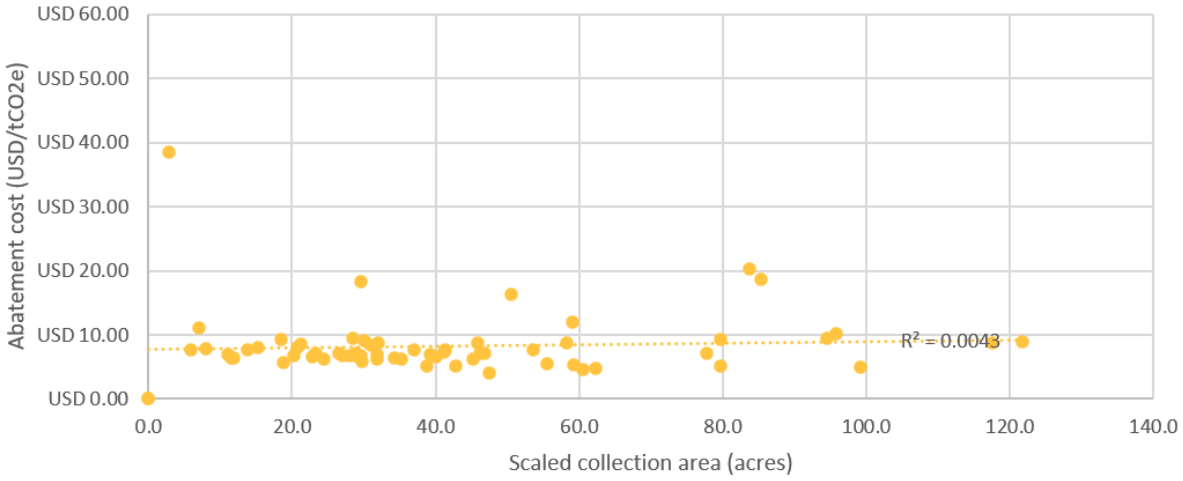
The highest-cost projects, including Baldan Recebimento de Resíduos da Construção Civil (18 USD/tCO_2e), Aterro Sanitário de Boa Vista (20 USD/tCO_2e), Aterro Sanitário do Município de Joinville (16 USD/tCO_2e), and CGA BARU (19 USD/tCO_2e), combine relatively modest mitigation potential of 1-3 $ktCH_4$/year with large landfill surface areas (29-80 acres).

Ecoparque Corpus - Unidade Indaiatuba represents a separate case. Its high abatement cost (38 USD/tCO_2e) is associated with a very small additional mitigation potential of approximately 0.23 $ktCH_4$/year, as the site is already achieving a high degree of methane capture. Consequently, even relatively modest additional costs result in a high cost per tonne of emissions avoided.

CTR Cachoeiro de Itapemirim (47 USD/tCO_2e) appears to be an outlier with an acreage of 1946, likely pointing to an error in the landfill characteristics data.

Overall, landfill area alone does not appear to be a strong predictor of abatement cost. Several large landfills achieve relatively low abatement costs where substantial methane reductions can be realised. Rather, the results indicate that the relationship between the scale of the required collection system and achievable mitigation potential is important for project economics. Excluding the outlier, the 5 highest-cost projects have a median land intensity of approximately 42 scaled acres per $ktCH_4$ mitigated, compared with approximately 6 scaled acres per $ktCH_4$ for the remainder of the portfolio.

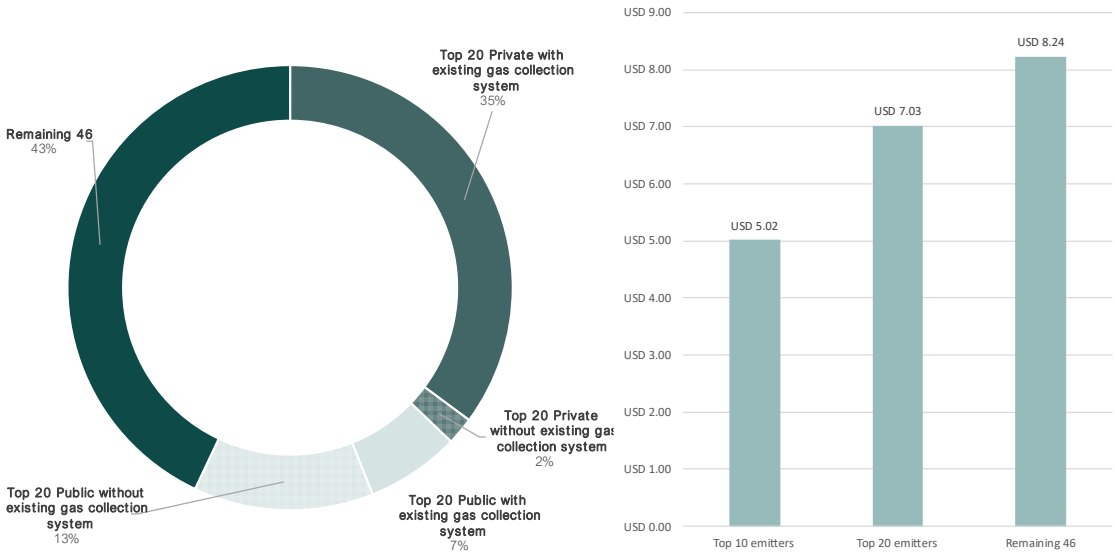
Figure 10 - Scatter plot of abatement costs and surface area for expansion of gas collection system per landfill (excluding acreage outlier)



A relatively small number of landfills account for a large share of the total mitigation potential. The top 10 sites account for 37% of total mitigation potential, with a weighted average abatement cost of 5.02 USD/tCO_2e, compared with 8.24 USD/tCO_2e for the remaining 56 sites. The top 20 emitting sites account for 57% of the total, with a weighted abatement cost of 7.03 USD/tCO_2e, slightly less than the 8.24 USD/tCO_2e estimated for the remaining sites.

Notably, 7 of the top 10 sites and 15 of the top 20 emitting sites already report landfill gas collection systems. This indicates that many of the highest-potential, lowest-cost mitigation opportunities are associated with large, established sites where significant methane reductions remain available despite the presence of existing collection infrastructure. Across the top-emitting sites, ownership was divided where 4 of the top 10 sites have private ownership whilst 13 of the top 20 sites are privately owned. Based on mitigation potentials, this splits the share of emissions to predominantly the private sector (36%) compared to the public sector (18%) for the top 20 emitting sites.

Figure 11 - Share of total mitigation potential for all sites (left) and abatement costs in USD per tonne CO_2e (right)



In total, 57 out of the 66 assessed landfill sites have abatement costs below 10 USD/tCO_2e, together accounting for 95% of the total mitigation potential. The results indicate that prioritising large, high-emitting

landfills could provide a cost-effective approach to reducing methane emissions, as a substantial share of the identified mitigation potential can be addressed at relatively low cost. Many of these sites are also among the largest methane emission sources identified in the analysis.

5 Discussion

5.1 Implications for methane mitigation in Brazil

The results suggest that landfill methane mitigation efforts in Brazil could initially focus on a relatively limited number of high-emitting landfills where substantial reductions can be achieved at comparatively low abatement costs. Prioritising these sites could provide a practical starting point for implementation, while experience gained through early projects could support subsequent mitigation efforts across a broader range of facilities.

Importantly, many of the largest mitigation opportunities identified in the analysis are associated with landfills where LFG collection systems are already in place. The presence of collection infrastructure should therefore not necessarily be interpreted as indicating that the available mitigation potential has already been addressed. The results highlight the importance of considering improvements to existing systems alongside the installation of new collection infrastructure.

For sites with higher abatement costs, additional sources of revenue or financial support could improve project economics. Carbon market revenues, climate finance, public support and revenues from LFG utilisation could therefore play a role in extending implementation beyond the lowest-cost opportunities identified in the analysis.

Although the results clearly identify a set of low-hanging fruit, they do not suggest that mitigation efforts should be limited exclusively to the largest and lowest-cost sites. Rather, the findings highlight the potential value of complementary financial and policy mechanisms that could expand implementation beyond the initial priority group. Many projects with moderate or higher abatement costs remain capable of delivering meaningful methane reductions, particularly where landfill gas utilisation revenues, climate funds, carbon market revenues, or public support mechanisms are available. Under favourable carbon market conditions, a substantial proportion of projects that currently appear marginal could become economically attractive. Carbon credits may be particularly relevant for landfill methane projects. Recent market information suggests that voluntary landfill gas credits may currently achieve prices above approximately 4.5 USD/tCO_2e, while credits authorised by the Brazilian government for use as Internationally Transferred Mitigation Outcomes (ITMOs) under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) could potentially achieve values in the range of approximately 13-15.5 USD /tCO_2e, subject to eligibility requirements and corresponding adjustment authorisation by Brazil.[35] Under such scenarios, carbon revenues could materially improve project economics and reduce effective abatement costs, particularly for projects that are currently close to economic viability based on energy revenues alone. Therefore, the negative NPVs reported for many projects should be viewed in the context of the assumptions applied and not necessarily as evidence that implementation would be commercially unattractive under all market conditions.

Finally, the study illustrates the value of adopting a measurement-informed methane mitigation strategy. Traditional inventory approaches remain essential for estimating national emissions, while the satellite observations demonstrate the ability of remote sensing technologies to identify individual high-emitting facilities and support prioritisation efforts. The combination of satellite observations, facility-level data, engineering assessments, and ongoing landfill gas collection system monitoring creates a practical

[35] Quantum Commodity Intelligence. (n.d.). *Quantum Commodity Intelligence*. Available at: https://www.qcintel.com/ (Accessed in September 2026)

framework for directing resources toward the most significant emission sources and verifying the effectiveness of mitigation actions over time. This is especially relevant within the super-emitter initiative in Brazil where the right combination of data can support transparency and effective mitigation where it is most impactful.

5.2 Comparison of modelled FOD emissions and observed Carbon Mapper emissions

The difference between the recovery-adjusted FOD estimates and Carbon Mapper observations likely reflects uncertainties and methodological differences associated with both approaches. The FOD model relies on assumptions regarding historical waste disposal, waste composition, methane generation potential (L_0), decay rates (k), and methane recovery performance, all of which influence estimated emissions. In addition, the FOD calculations performed in this study did not include methane oxidation in landfill cover soils, which contributed to some overestimation of emissions, particularly at well-managed landfills with established cover systems.

At the same time, Carbon Mapper observations may underestimate total emissions because they primarily quantify detectable methane plumes and may not fully capture diffuse emissions, low-concentration releases, or emissions occurring outside satellite observation periods.

The results therefore suggest that the true emissions may lie between the modelled and observation-based estimates for many sites. While the recovery-adjusted FOD estimates show reasonable agreement with the managed-landfill component of Brazil's national inventory, there are still significant differences between the methods. Therefore, considering the two approaches together can help identify sites where emission estimates diverge substantially and where further investigation or improved site-specific data may be particularly valuable.

5.3 Impact of alternative landfill management practices

Landfill methane emissions are influenced by a range of management practices beyond landfill gas (LFG) collection. These measures can reduce methane generation, increase methane oxidation, or improve gas capture by limiting fugitive emissions. Because these mechanisms interact, their impacts should not be added directly to the mitigation potential estimated for improved LFG collection systems. Measures that reduce methane generation also reduce the quantity of gas available for recovery, while measures that improve operational performance can increase collection efficiency.[36, 37]

The first-order decay (FOD) model captures some of these effects through parameters such as the Methane Correction Factor (MCF) and oxidation factor (OX), but many important operational drivers of emissions are not explicitly represented. Factors including cover integrity, working-face management, moisture conditions, drainage performance, gas migration pathways and collection system downtime can strongly influence emissions while remaining outside the scope of conventional FOD modelling.[38] Consequently, FOD is well suited for estimating long-term methane generation but is less effective for predicting site-specific operational emissions and super-emitter events identified through remote sensing.

[36] Intergovernmental Panel on Climate Change. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste, Chapter 3: Solid Waste Disposal*. Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_3_Ch03_SWDS.pdf (Accessed in September 2026)

[37] U.S. Environmental Protection Agency. (2024a). *LFG Energy Project Development Handbook*. Landfill Methane Outreach Program. Available at: https://www.epa.gov/lmop/landfill-gas-energy-project-development-handbook (Accessed in September 2026)

[38] Krause, M.J. (2018). Intergovernmental Panel on Climate Change's landfill methane protocol: Reviewing 20 years of application. *Waste Management & Research*, 36(9), 827–840. Available at: https://www.swa.org/DocumentCenter/View/6472/Intergovernmental-panel-on-climate-changes-landfill-methane-protocol-Reviewing-20-years-of-application?bidId= (Accessed in September 2026)

For the Brazilian landfill portfolio assessed in this study, the most relevant alternative measures are likely to be those that improve the performance of existing gas collection systems. Of the assessed sites, 50% report gas collection infrastructure, yet these sites account for a large share of observed methane emissions, indicating substantial opportunities for optimisation. Measures such as improved cover systems, minimisation of active working faces, better drainage management, timely expansion of collection networks, and enhanced operation and maintenance can reduce fugitive emissions while improving methane recovery.[39] [40] This observation is consistent with the finding that many of the largest mitigation opportunities occur at landfills where collection systems are already present but not operating at their full potential.

Other management approaches, including biocovers, semi-aerobic operation, active aeration and organic waste diversion, may also reduce emissions under suitable conditions. However, unlike measures that improve gas capture, these approaches generally reduce methane generation and may therefore decrease the quantity of gas available for energy recovery or biomethane production. Their suitability should therefore be assessed on a site-specific basis, taking into account both emission reduction objectives and the technical and economic feasibility of landfill gas utilisation.

Overall, alternative landfill management practices should be viewed as complementary to landfill gas collection rather than independent mitigation measures. Their effects should not be directly added to the estimated mitigation potential for LFG collection because this would risk double-counting reductions. Instead, FOD modelling, remote observations such as Carbon Mapper, and site-specific engineering assessments should be used together to evaluate integrated mitigation strategies and identify the most appropriate combination of measures for each landfill.

5.4 Co-benefits of landfill gas collection

Beyond the financial returns and climate mitigation, improving landfill gas capture and associated management practices at Brazilian sites can deliver substantial public health and air quality benefits, as capturing and destroying the gas reduces emissions of volatile organic compounds, odours, and the tropospheric ozone precursors that affect local air quality.[41] A recent Brazilian study of a sanitary landfill in Maringá confirms that controlled biogas recovery measurably reduces population exposure to these harmful pollutants, a benefit that is particularly valuable given the number of sites still operating as controlled or open dumps.[42] In addition, the removal of sulfur compounds such as hydrogen sulfide reduces the odours that are a persistent source of community complaints near landfill sites.[43]

[39] Scarpelli, T.R. et al. (2024). Investigating major sources of methane emissions at US landfills. *Environmental Science & Technology*, 58, 21545–21556. Available at: https://pubs.acs.org/esthag/article-pdf/58/49/21545/1686035/es4c07572.pdf (Accessed in September 2026)

[40] *Environmental Research & Education Foundation (EREF) (2025). Critical Analysis of Literature on Landfill Gas Collection Efficiency. Environmental Research & Education Foundation. Available at: www.erefdn.org*

[41] US EPA (2026). *Benefits of Landfill Gas Energy Projects.* Landfill Methane Outreach Program (LMOP). Available at: https://www.epa.gov/lmop/benefits-landfill-gas-energy-projects (Accessed in September 2026)

[42] Nazzari, E. C., et al. (2026). *From Waste to Health: Landfill Biogas Recovery as a Strategy for Greenhouse Gas Mitigation and Public Health Co-Benefits in Brazil.* International Journal of Environmental Research and Public Health, 23(5), 648. Available at: https://www.mdpi.com/1660-4601/23/5/648 (Accessed in September 2026)

[43] Pecorini, I., et al. (2020). *Mitigation of Methane, NMVOCs and Odor Emissions in Active and Passive Biofiltration Systems at Municipal Solid Waste Landfills.* Sustainability, 12(8), 3203. Available at: https://www.mdpi.com/2071-1050/12/8/3203 (Accessed in September 2026)

6 Conclusions

This study assessed the methane mitigation potential of 66 landfill sites in Brazil identified through satellite observations provided by Carbon Mapper. By combining observation-based methane emissions, landfill-specific information, FOD modelling, and economic analysis, the study provides a screening-level assessment of the scale, cost, and distribution of methane mitigation opportunities across a significant subset of Brazil's waste sector.

The results indicate that the assessed portfolio represents a substantial source of methane emissions. Annualised Carbon Mapper observations estimate emissions of approximately 642 $ktCH_4$/year, equivalent to around 29% of the methane emissions reported for Brazil's waste final disposal sector, despite representing only 66 out of 1005 (6.6%) sanitary- and controlled landfill facilities nationwide. These findings confirm that methane emissions are highly concentrated among a limited number of large super-emitting landfills and demonstrate the value of satellite-based observations for identifying priority mitigation opportunities.

The analysis estimates that approximately 456 $ktCH_4$/year of observed emissions could be mitigated through improved landfill gas management, corresponding to around 71% of observed emissions from the assessed sites and around 20% of Brazil's reported solid waste emissions for 2024. Importantly, the majority of this mitigation potential is associated with landfills where gas collection infrastructure already exists. Approximately 266 $ktCH_4$/year of mitigation potential is associated with sites that already report landfill gas collection systems, while 189 $ktCH_4$/year is associated with sites where collection infrastructure would need to be installed. This finding highlights that substantial methane reductions can be achieved not only through the deployment of new systems, but also through optimisation, expansion, and improved operation of existing infrastructure.

The mitigation opportunities identified in this study are largely associated with a relatively small number of sites. The top 10 sites account for 37% of the total estimated mitigation potential, while the top 20 emitting sites account for 57%. Furthermore, these sites have substantially lower weighted average abatement costs than the remainder of the assessed sites. More broadly, 57 of the 66 assessed sites have estimated abatement costs below 10 USD/tCO_2e and account for approximately 95% of the total mitigation potential. Larger landfill gas projects generally have lower abatement costs, reflecting economies of scale and the ability to spread infrastructure costs across larger methane recovery volumes. These results suggest that prioritising high-potential, low-cost landfills could deliver a substantial share of the identified methane reductions at relatively low cost.

The comparison between FOD-modelled emissions and Carbon Mapper observations demonstrates the importance of combining multiple approaches when evaluating landfill methane emissions. The FOD model estimated approximately 1,444 $ktCH_4$/year of emissions across the assessed portfolio, substantially higher than the 642 $ktCH_4$/year derived from Carbon Mapper observations. The observed differences reflect a combination of fundamentally different approaches to characterising landfill emissions and general uncertainties associated with both approaches, including limitations in satellite detection and simplifications inherent in modelling methodologies. The results therefore highlight the value of integrating both top-down observations, bottom-up modelling, and site-level measurements to improve methane inventories and support mitigation planning.

Overall, the findings demonstrate that landfill methane mitigation represents a significant and largely accessible opportunity for reducing greenhouse gas emissions in Brazil. The combination of substantial mitigation potential, relatively low abatement costs, and the concentration of opportunities at a limited number of large facilities creates favourable conditions for rapid emissions reductions. By prioritising high-emitting landfills, improving the performance of existing gas collection systems, as well as leveraging measurement-based monitoring approaches, Brazil could achieve meaningful near-term methane reductions while generating additional environmental, public health, and energy recovery benefits. Beyond

the scope of this study, the proposed measures should be considered in parallel with upstream measures that are aimed at reducing waste generation and diverting waste disposal to achieve long-term reductions in methane emissions within the waste sector.

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