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# Integrated methane capture system with isometric pipeline network in the refuse derived fuel plant

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**Abstract:** Landfills remain one of the largest anthropogenic sources of methane ($CH_4$), a potent greenhouse gas with significant climate impact. Effective capture and utilisation of landfill gas are therefore essential to reduce emissions while supporting renewable energy recovery. This study presents the integrated design of a methane gas capture system with an isometric pipeline network in the Jeruklegi refuse derived fuel (RDF) plant, Cilacap. The research aimed to optimise methane recovery through technical evaluation of pipeline configuration, head loss calculations, and compressor specifications. The methodology included estimating methane generation potential using the landfill gas emissions model (LandGEM) and Intergovernmental Panel on Climate Change (IPCC) guidelines, calculating major and minor head losses in a 160 mm pipeline system, and determining blower requirements. The potential methane production was estimated at approximately $2.78 \cdot 10^6$ $m^3 \cdot y^{-1}$, while the designed collection system could capture around $2.06 \cdot 10^6$ $m^3 \cdot y^{-1}$. This corresponds to a capture efficiency of nearly 75%, which aligns with international benchmarks for modern landfill gas systems (60–85%). The required blower capacity was determined to be ≥320 $m^3 \cdot h^{-1}$ at a vacuum pressure of from −10,000 to −20,000 Pa, with an optimal power range of 1–2.2 kW, indicating that larger units (4–5 kW) would be oversized and inefficient. The findings highlight the feasibility of applying an integrated gas capture system in RDF plants to mitigate greenhouse gas emissions while ensuring energy recovery. This work provides a practical engineering reference for sustainable landfill gas management and supports the transition toward low-carbon waste treatment technologies.

**Keywords:** controlled landfill, greenhouse gas, head loss, landfill gas, methane capture, pipeline design, waste management

## INTRODUCTION

Indonesia generates approximately 35 mln Mg of waste annually, with around 60.11% remaining unmanaged (Kementerian Lingkungan Hidup dan Kehutanan, 2024). In urban areas, landfill disposal dominates, where anaerobic decomposition produces methane ($CH_4$) – a greenhouse gas with a significantly higher global warming potential than carbon dioxide ($CO_2$) (LCDI, Kementerian PPN/Bappenas, 2023).

Broadly, there are two main landfill types in Indonesia: open dumping and sanitary landfill. In 2024, about 6.7 mln Mg of waste were disposed of in open dumping sites and 8.5 mln Mg in sanitary landfills (Kementerian Lingkungan Hidup dan Kehutanan, 2024). Open dumping refers to the uncontrolled disposal of waste, where waste is piled without treatment, resulting in uncontrolled pollution and greenhouse gas emissions (Ferronato and Torretta, 2019). By contrast, sanitary landfills are more controlled, where waste is systematically layered, compacted, and covered, equipped with leachate and gas management systems (Kulkarni, 2020).

Although sanitary landfills are more environmentally sound than open dumping, anaerobic processes still generate methane that contributes significantly to global warming if not captured or utilised effectively (Sari *et al.*, 2025). Therefore, developing landfill gas (LFG) capture technologies and improving waste recycling systems are crucial strategies to reduce greenhouse gas emissions from the waste sector.

In response to this challenge, the Cilacap Regency Government has developed a city-scale waste management system using the controlled landfill method. This approach shifts the conventional paradigm of "collect–transport–dispose" into a more sustainable framework of "collect–transport–sort–process–landfill".

The Jeruklegi landfill, covering 3.2 ha, is now classified as a passive landfill site (Syahni, 2022). Compared with conventional landfills or open dumping, sanitary landfill systems provide greater social and environmental benefits, particularly in reducing air and water pollution. However, the drawback remains that methane continues to be generated from decomposing organic matter (Nursetyowati *et al.*, 2024). To mitigate this, an efficient methane gas collection system is required to capture and process methane into useful energy, such as electricity, while simultaneously reducing greenhouse gas emissions (Prawisudha and Low Carbon Development Indonesia, 2022).

Methane ($CH_4$) is among the most potent greenhouse gases, with a global warming potential far greater than $CO_2$ over long time horizons (Sari, Fadiilah and Azizi, 2019). The primary source of methane in landfills is anaerobic decomposition of organic waste, derived from domestic, industrial, and agricultural origins (Nursetyowati *et al.*, 2024). Many landfill sites in Indonesia still lack efficient methane capture and management systems, leading to significant emissions. Methane capture not only reduces environmental impacts but also provides opportunities to harness an alternative and valuable energy source (Sari *et al.*, 2019).

Designing an effective methane collection pipeline network is therefore critical to optimising gas capture. For a landfill area of approximately 6.3 ha, careful consideration is needed in selecting pipe materials, pipe dimensions, and system configurations to ensure efficiency and sustainability.

This study aims to contribute to sustainable waste management practices by analysing and designing a methane capture system tailored for the Jeruklegi landfill. The research further provides technical recommendations that can be implemented in practice, offering real solutions for methane gas management in landfill sites. Ultimately, this work supports governmental and community efforts in addressing climate change challenges while promoting environmental sustainability.

## MATERIALS AND METHODS

This research focuses on the integrated design of a methane gas capture system with an isometric pipeline network at the refuse derived fuel (RDF) plant in Cilacap, Indonesia. The study site is the Jeruklegi landfill, located in Cilacap Regency, Central Java, covering an area of approximately 6.3 ha (Kementerian Lingkungan Hidup dan Kehutanan, 2017). The landfill applies a controlled landfill system, which is a more modern and environmentally friendly approach to waste management that includes leachate and landfill gas control. Geographic conditions, waste composition, and waste volume play a significant role in influencing the design of the methane gas capture system.

Based on field observations and secondary data, the waste composition at Jeruklegi landfill consists of 60% organic and 40% inorganic waste, with an average daily disposal of 114.52 Mg (Prawisudha and Low Carbon Development Indonesia, 2022). These conditions suggest considerable potential for methane generation, which provides the basis for determining well density and the spatial arrangement of the gas collection system.

The methodology involves spatial analysis for well placement, estimation of methane generation, hydraulic and pipeline design, and system visualisation using engineering software. The conceptual framework for this research is illustrated in Figure 1 below.

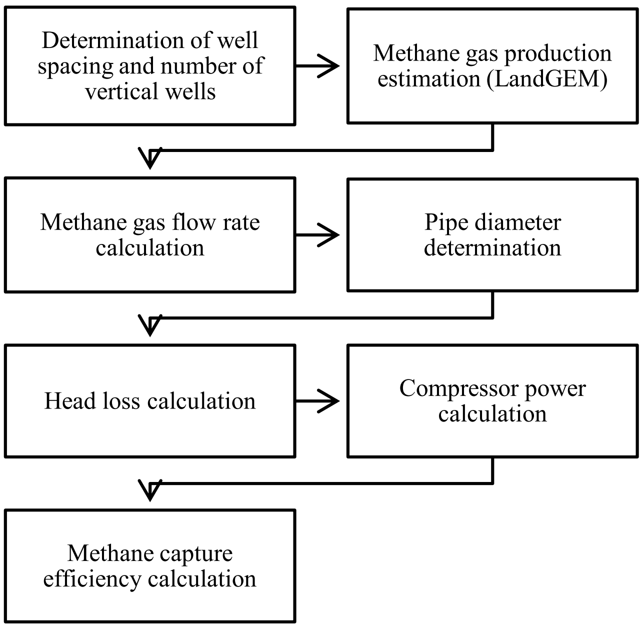


**Fig. 1.** Research framework; source: own elaboration

- **Determination of well spacing and number of vertical wells**

The primary data in this study were collected directly by the researcher through measurements and observations. These data are specific in nature and designed to directly address the research questions. Spacing between wells was determined based on the assumption from numerical studies, which indicate that the radius of influence (zone of influence) of vertical wells ranges from approximately 38,000 to 67,000 mm.

$$N = \frac{A}{S^2} \tag{1}$$

where: $N$ = number of vertical wells required, $A$ = landfill area ($m^2$), $S$ = spacing between wells in a grid pattern (m).

- **Methane generation estimation**

The US EPA LandGEM Model (Version 3.02) was used to estimate methane generation potential. Methane production over time is calculated as follows (Tchobanoglous, Theisen and Vigil, 1993; US EPA, 2023):

$$Qt = \sum_{i=1}^{n} (Lo \cdot Ri \cdot e^{-k(t-i)}) \tag{2}$$

where: $Qt$ = methane generation at year $t$ ($m^3 \cdot y^{-1}$), $Lo$ = potential methane generation capacity ($m^3 \cdot Mg^{-1}$), $Ri$ = waste mass disposed in year $i$ (Mg), $k$ = first-order decay rate constant ($1 \cdot y^{-1}$), $t$ = year of calculation, $n$ = number of disposal years.

- **Gas flow rate calculation**

According to White (2016), the methane gas flow rate is determined as follows:

$$Q = A \cdot v \tag{3}$$

where: $Q$ = flow rate ($m^3 \cdot s^{-1}$), $A$ = cross-sectional area of the pipe, $v$ = gas velocity ($m \cdot s^{-1}$).

$$A = \frac{\pi \cdot D^2}{4} \tag{4}$$

where: $D$ = pipe diameter (m).

- **Head loss in piping system**

According to Çengel and Cimbala (2006), head loss in a piping system is calculated using the Darcy–Weisbach equation as follows:

$$hf = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \tag{5}$$

where: $hf$ = head loss (m), $f$ = friction factor (Moody chart), $L$ = pipe length (m), $v$ = gas velocity ($m \cdot s^{-1}$), $g$ = acceleration due to gravity (9.81 $m \cdot s^{-2}$).

$$h_m = K \cdot \frac{v^2}{2g} \tag{6}$$

where: $h_m$ = minor head loss, $K$ = minor loss coefficient.

- **Compressor power requirement**

According to Karassik *et al.* (2007), the power requirement is calculated as follows:

$$P = \frac{\rho \cdot g \cdot H \cdot Q}{\eta} \tag{7}$$

where: $P$ = power, $\rho$ = methane gas density (0.716 $kg \cdot m^{-3}$), $H$ = head total (128.2 m), $Q$ = 0.08818 $m^3 \cdot s^{-1}$, $\eta$ = system efficiency (0.6 for blower vacuum system).

- **Gas capture efficiency**

The efficiency of methane capture is calculated as follows (IPCC, 2006; Scheutz and Kjeldsen, 2019):

$$\eta = \frac{V_{\text{captur}}}{V_{\text{total}}} \cdot 100\% \tag{8}$$

where: $\eta$ = capture efficiency (%), $V_{\text{captur}}$ = capture methane volume ($m^3$), $V_{\text{total}}$ = total methane production ($m^3$).

The target efficiency is 60–85%, consistent with US EPA and international best practices (US EPA, 2024).

To support the design process, both field surveys and software tools were employed. Field surveys were conducted using QGIS and Google Earth to map and mark the planned extraction well points with stakes. During the design stage, AutoCAD was applied to draft the technical drawings of vertical and horizontal pipeline networks on separate layers, as well as to generate plan views, cross-sections, and detailed manifold and flaring system layouts. SketchUp was used to create 3D visualisations of the pipeline network, wells, manifold, and flare system, providing a spatial representation of the landfill infrastructure. LandGEM was utilised to estimate methane generation rates and overall landfill gas production, thereby determining the required number of extraction wells. Finally, QGIS supported spatial mapping of well coordinates, enabling grid optimisation and seamless integration with AutoCAD layouts.

## RESULTS AND DISCUSSION

The calculation of the number of vertical wells was carried out using a grid approach with optimal spacing between wells. This approach ensures methane gas collection in accordance with the system configuration. In this design, the well depth was set at 10,000 mm to reach the bottom of the waste layer.

**Table 1.** Recommended practice for well density

| Well density | Area per well ($m^2$) | Typical application |
|---|---|---|
| Low (sparse) | >1,500 | new or dry landfill sites |
| Medium (common) | 900–1,200 | active and moist landfills |
| High (dense) | <800 | high gas production, intensive systems |

Source: US EPA (2020).

Following the Equation (1), the total landfill area is 63,000 $m^2$, and with a grid size of 36 × 36 m, each well covers 1,296 $m^2$, requiring approximately 48 vertical wells. Alternative layouts, such as 30 × 30 m (dense) or 37 × 37 m (sparse), demonstrate design flexibility based on site conditions. The proposed spacing falls within the "moderate" category recommended by the United States Environmental Protection Agency (US EPA) and CalRecycle guidelines (US EPA, 2023).

This configuration is consistent with practices for active and moist landfills, where closer well spacing improves gas collection efficiency and minimises fugitive emissions (US EPA, 2020; Anh *et al.*, 2021).

Studies indicate that moderate spacing optimises both cost and methane recovery, while overly dense grids increase installation costs without significant efficiency gains (Putro and Wahid, 2020). Furthermore, well density influences methane capture rates, which directly affect greenhouse gas mitigation and energy recovery potential (Kasala *et al.*, 2025). A summary of the land area and methane pipe units is presented in Table 2. Therefore, the proposed configuration of 48 wells is technically feasible and consistent with best practices, as illustrated in Figure 2.

Methane generation was estimated using the LandGEM model with the following parameters in Table 3.

The simulation results indicate that peak methane production occurs in the fifth year, with an estimated volume of

**Table 2.** Summary of land area and methane pipe distribution

| Legend | Information | Land area ($m^3$) | Number of methane pipes (unit) |
|---|---|---|---|
| A | pavilion | 5,334 | 20 |
| B | plaza / jogging track | 5,602 | 2 |
| C | restaurant | 2,668 | 8 |
| D | theatre | 2,257 | – |
| E | ship garden | 910 | – |
| F | methane gas station | 1,370 | 1 |
| G | farmer's village | 2,315 | – |
| H | stool area | 715 | – |
| I | Kehati garden | 2,540 | 11 |
| J | maze garden | 11,044 | 1 |
| K | car park | 10,076 | – |

Source: own elaboration.

approximately 150,000 $m^3 \cdot y^{-1}$. This methane amount could be utilised for electricity, providing energy and environmental benefits (Wrzesińska-Jędrusiak *et al.*, 2024). The estimated methane volume at peak production highlights the potential for energy recovery through electricity generation, which can provide both environmental and economic benefits by reducing greenhouse gas emissions and offsetting fossil fuel use (Algarni *et al.*, 2023).

This result serves as the main reference for determining the pipeline capacity and the number of wells required to ensure efficient gas capture, as inadequate infrastructure could lead to fugitive emissions and reduced recovery efficiency (Wang *et al.*, 2022). Furthermore, the spatial arrangement of the wells designed based on this estimation is presented in Figure 2, which illustrates the layout of the gas collection wells.

The estimation of methane generation was conducted using the LandGEM model by incorporating site-specific waste deposition data and standard model parameters. The waste acceptance rate, which forms the primary input for methane generation calculations, is presented in Table 4.

The cumulative waste-in-place values presented in Table 4 are critical for modelling methane generation, as methane production is directly proportional to the mass of waste deposited and its decomposition over time. By 2020, the landfill had accumulated 174,600 Mg of waste, and projections indicate an increase to 595,440 Mg by 2027. This growth significantly influences the temporal distribution of methane emissions, as higher waste volumes accelerate anaerobic decomposition and gas formation (Anh *et al.*, 2021; Wrzesińska-Jędrusiak *et al.*, 2024).

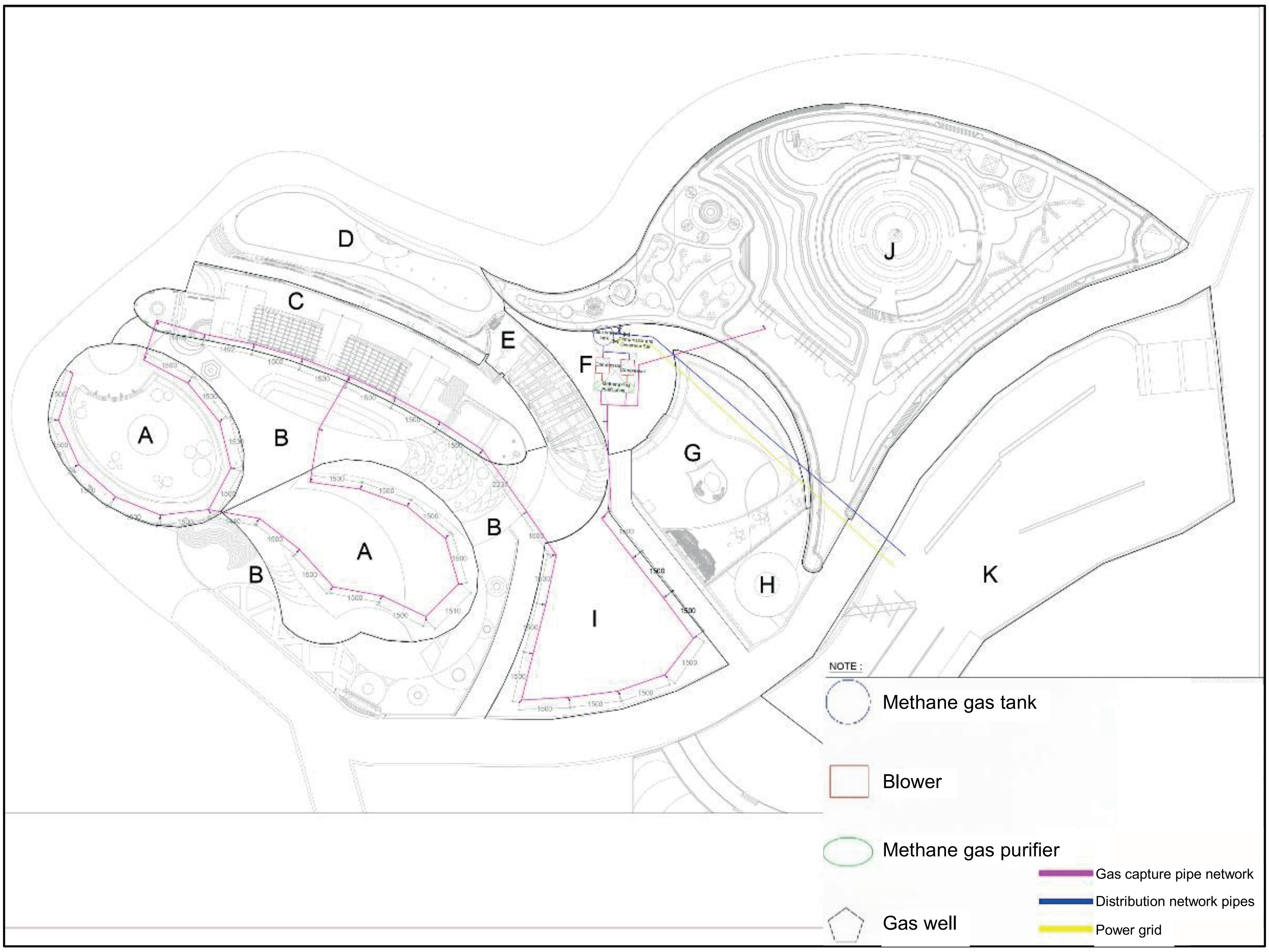


**Fig. 2.** Well location plan; A, B, C, D, E, F, G, H, I, J, K as in Tab. 2; source: own study

**Table 3.** LandGEM parameter

| Parameter | Value |
|---|---|
| Methane generation potential (*Lo*) ($m^3 \cdot Mg^{-1}$) | 170 |
| Decay rate constant (*k*) under tropical conditions (y) | 0.05–0.07 |
| Waste deposition rate ($Mg \cdot y^{-1}$) | 10,000 |
| Landfill operation period (y) | 10 |
| Start year of waste deposition | 2020 |

Source: own study.

**Table 4.** Waste accepted rate

| Year | Waste accepted | | Waste-in-place | |
|---|---|---|---|---|
| | $Mg \cdot y^{-1}$ | short tons$\cdot y^{-1}$ | Mg | short tons |
| 2017 | 57,600 | 63,492 | 0 | 0 |
| 2018 | 58,320 | 64,286 | 57,600 | 63,492 |
| 2019 | 58,680 | 64,683 | 115,920 | 127,779 |
| 2020 | 59,040 | 65,080 | 174,600 | 192,462 |
| 2021 | 59,400 | 65,477 | 233,640 | 257,541 |
| 2022 | 59,760 | 65,873 | 293,040 | 323,018 |
| 2023 | 60,120 | 66,270 | 352,800 | 388,891 |
| 2024 | 60,480 | 66,667 | 412,920 | 455,162 |
| 2025 | 60,840 | 67,064 | 473,400 | 521,829 |
| 2026 | 61,200 | 67,461 | 534,240 | 588,893 |
| 2027 | 61,560 | 67,858 | 595,440 | 656,354 |

Explanations: 1 short ton = 907.2 kg, consistent with the unit convention applied in the LandGEM model.
Source: own study.

This cumulative figure serves as a key input for the LandGEM model, as methane production is directly proportional to the mass of waste deposited and its decomposition over time.

The foundational dataset for modelling methane generation is provided in Table 5, where the annual deposition rate influences the temporal distribution of methane emissions, and the cumulative waste-in-place determines the overall landfill gas potential.

**Table 5.** Gas/pollutant default parameter

| Compound | Concentrate ion (ppmv) | Molecular weight |
|---|---|---|
| Total landfill gas | 1,000,000 | 30.03 |
| Methane | 500,000 | 16.04 |
| Carbon dioxide | 500,000 | 44.01 |
| NMOC | 4,000 | 86.18 |

Explanations: NMOC = non-methane organic compounds.
Source: own study.

The LandGEM model, which incorporates these cumulative figures along with default gas generation parameters (Tab. 5), has been widely applied for estimating landfill gas potential and planning recovery systems (Saeedi *et al.*, 2025). Accurate estimation of waste-in-place is essential for designing gas collection infrastructure, as underestimating waste mass can lead to insufficient well capacity and pipeline sizing, reducing capture efficiency and increasing fugitive emissions (Wang *et al.*, 2022). Furthermore, integrating site-specific waste acceptance rates into the model improves prediction accuracy compared to using generic defaults, which often fail to account for regional variations in waste composition and moisture content (Anh *et al.*, 2021). These considerations highlight the importance of robust data collection and modelling for sustainable landfill management and effective methane recovery.

The default parameters of landfill gas composition are presented in Table 5. The total landfill gas is assumed to consist of 50% methane and 50% carbon dioxide, with a small fraction of non-methane organic compounds (NMOC) at 4,000 ppmv (US EPA, 2020). Methane, with a relatively low molecular weight (16.04 $g \cdot mol^{-1}$), represents the primary contributor to greenhouse gas potential, while $CO_2$ (44.01 $g \cdot mol^{-1}$) dominates the mass fraction due to its higher molecular weight. Although NMOCs account for only 0.4% of the gas mixture, their high molecular weight (86.18 $g \cdot mol^{-1}$) and pollutant characteristics highlight their relevance in assessing air quality impacts and secondary pollutant formation. These default values are essential for converting volumetric concentrations into mass-based emission estimates and serve as standard input for landfill gas models such as LandGEM.

Based on these inputs, the simulation produced the methane generation curve as illustrated in Figure 3, showing the temporal

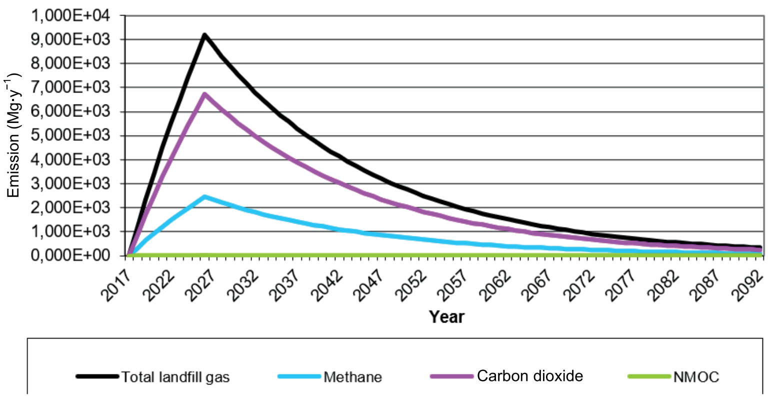


**Fig. 3.** Methane graph from LandGEM; NMOC as in Tab. 5; source: own study

trend and peak of methane emissions during the operational period of the landfill.

The methane flow rate was calculated using Equation (2) with the following parameters: waste mass disposed in year $i$ ($Ri$) = 61,560 $Mg \cdot y^{-1}$, potential methane generation capacity ($Lo$) = 170 $m^3 \cdot Mg^{-1}$, first-order decay rate constant ($k$) = $0.05 \cdot y^{-1}$, for six years. Using these values, the basic constant was determined as 523,260 $m^3 \cdot y^{-1}$. Based on this, the cumulative methane production over six years was estimated at 2,780,763.76 $m^3$ as presented in Table 6.

**Table 6.** Gas flow rate calculation ($Qt$) value

| $i$ | $t–i$ | $e^{(-k(t-i))}$ | $Qi$ ($m^3$) |
|---|---|---|---|
| 1 | 5 | $e^{-0.25}$ = 0.778801 | 407,515.41 |
| 2 | 4 | $e^{-0.2}$ = 0.818731 | 428,409.18 |
| 3 | 3 | $e^{-0.15}$ = 0.860708 | 450,374.06 |
| 4 | 2 | $e^{-0.1}$ = 0.904837 | 473,465.01 |
| 5 | 1 | $e^{-0.05}$ = 0.951229 | 497,740.08 |
| 6 | 0 | $e^{0}$ = 1 | 523,260 |
| **Total** | | | **2,780,763.76** |

Explanations: $i$ = year when the waste was disposed, $t$ = year when the gas generation was calculated, $k$ = first-order decay rate constant.
Source: own study.

This corresponds to an average flow rate of approximately 7,618.53 $m^3 \cdot y^{-1}$, or 317.44 $m^3 \cdot h^{-1}$, which is equivalent to 0.08818 $m^3 \cdot s^{-1}$. These results indicate a substantial methane generation potential from the landfill during the initial operational period.

The decay constant suggests a moderate degradation rate, consistent with typical conditions for mixed waste in tropical climates. The calculated flow rates demonstrate that the landfill could support energy recovery initiatives or flaring systems to mitigate greenhouse gas emissions.

Thus, in the sixth year, methane production potential reached approximately 2.78 mln $m^3 \cdot y^{-1}$, equivalent to a continuous flow of 0.088 $m^3 \cdot s^{-1}$. This result indicates a substantial methane generation capacity, consistent with expected values for municipal solid waste landfills under LandGEM parameters. The magnitude of production suggests significant potential for energy recovery if methane is captured, while also highlighting the importance of adequate gas management to mitigate greenhouse gas emissions. Moreover, this finding underscores the importance of localised modelling for accurate landfill gas (LFG) predictions, particularly in tropical regions where waste composition and climatic conditions differ from temperate zones (Anh *et al.*, 2021).

Using the US EPA default LandGEM parameters ($Lo$ = 100 $m^3 \cdot Mg^{-1}$, $k$ = $0.04 \cdot y^{-1}$) for the same input mass ($Ri$ = 61,560 $Mg \cdot y^{-1}$) and a six-year period, methane generation was lower, with total production estimated at 1,746,113.81 $m^3 \cdot y^{-1}$, equivalent to a flow rate of 0.055 $m^3 \cdot s^{-1}$ (US EPA, 2023)

In contrast, applying the site-specific parameters in this study ($Lo$ = 170 $m^3 \cdot Mg^{-1}$, $k$ = $0.05 \cdot y^{-1}$) resulted in a total methane production of 2,780,763.76 $m^3 \cdot y^{-1}$ or 0.088 $m^3 \cdot s^{-1}$. This represents an increase of approximately 59% compared to the US EPA default case, highlighting the importance of using localised parameters for more accurate methane generation estimates.

The higher methane yield indicates that the waste characteristics and climatic conditions at the studied landfill support greater biodegradability and gas generation potential than the generic US EPA assumptions. This emphasises the importance of using site-specific parameters rather than default values for more accurate emission and energy recovery assessments.

The distribution pipe diameter ($D$) was calculated using Equation (4), with the landfill gas flow rate obtained from the previous methane generation analysis, which was 0.08818 $m^3 \cdot s^{-1}$.

The gas velocity ($v$) was assumed based on internationally recognised best practice guidelines. According to the Global Methane Initiative (US EPA, 2012).

Guidelines form EPA LMOP handbook (US EPA, 2024), a conservative design velocity of 3–5 $m \cdot s^{-1}$ is recommended in the header pipe to minimise pressure drop, erosion, condensate entrainment, and backpressure. Similarly, (SWANA, 1997) recommends 3–4.6 $m \cdot s^{-1}$ in headers, while (NFPA, 2025) codes suggest ≤5 $m \cdot s^{-1}$ for low-pressure gas systems.

A velocity of 4 $m \cdot s^{-1}$ was selected as a safe and practical design value. Based on this assumption, the calculated pipe diameter using Equation (4) is approximately 166.5 mm, which is equivalent to about 6.5 inches or rounded to 6 inches. This size is considered suitable for maintaining the desired gas flow while ensuring structural integrity and operational efficiency.

The result shows that a 6-inch pipe is suitable for the landfill gas distribution system, as it meets international design standards for maintaining stable gas flow while preventing turbulence and operational issues. An isometric schematic of the designed pipe diameter is shown in Figure 4.

The calculation of major head loss requires several parameters from the previous steps, one of the most important being the pipe material, since this determines the friction factor value. The selection of pipe material was conducted using a scoring method, commonly applied in multi-criteria decision analysis (MCDA) or weighted scoring methods, where each criterion is assigned a weight, and each material is scored (e.g., on a scale of 1 to 5). The scoring shown in Table 7 compares HDPE (high-density polyethylene) and PVC (polyvinyl chloride), and carbon steel pipes.

Based on the results, HDPE was selected as the preferred pipe material. Pipes made of HDPE performed best in terms of corrosion resistance, installation flexibility, and maintenance requirements.

In comparison, PVC offers advantages in terms of lower initial cost and availability but is only suitable for low-pressure applications. Carbon steel pipes, while superior in mechanical strength and durability, were less favourable due to their susceptibility to corrosion and higher costs.

With the material selected, the major head loss was calculated using the Darcy–Weisbach approach, as shown in Equation (5), and the general criteria used for pipe assessment are presented in Table 8.

For a 6-inch pipe with a length of 101,000 mm, the major head loss was determined to be approximately 15,400 mm. The minor head loss was also calculated for each type of fitting based on the reference coefficients. The parameters used included

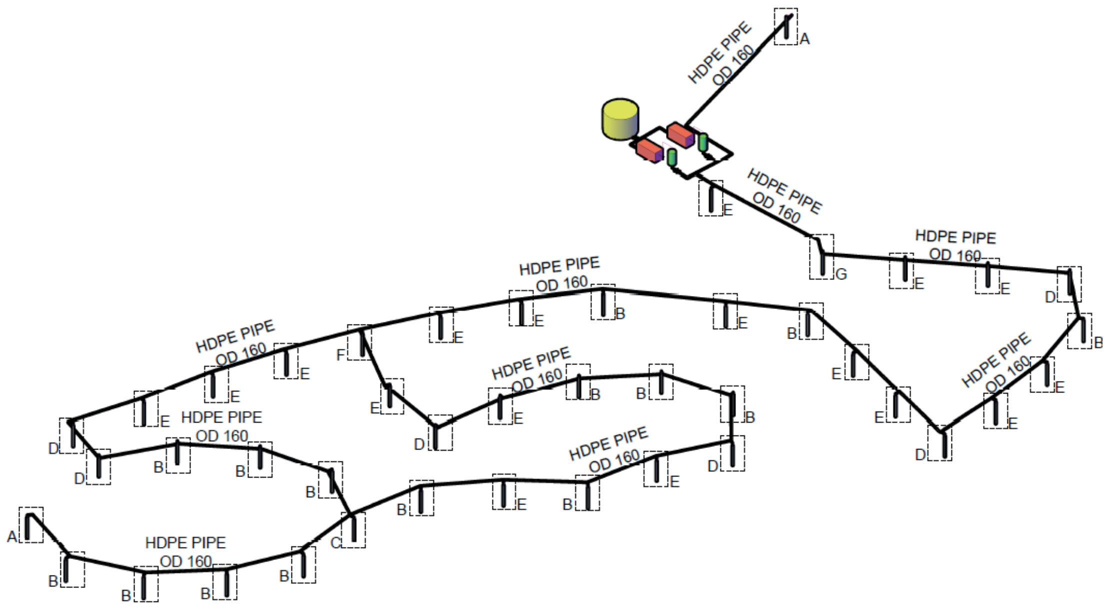


**Fig. 4.** Isometric diameter of the pipe system; HDPE = high-density polyethylene, OD = outside diameter, A, B, C, D, E, F, G = detail junction; source: own study

**Table 7.** High-density polyethylene (HDPE), polyvinyl chloride (PVC), and carbon steel pipe scoring

| Criteria | Weight (%) | Score | | | Total score | | |
|---|---|---|---|---|---|---|---|
| | | HDPE | PVC | steel | HDPE | PVC | steel |
| Corrosion and chemical resistance | 25 | 5 | 4 | 2 | 125 | 100 | 50 |
| Mechanical strength / compression | 20 | 4 | 3 | 5 | 80 | 60 | 100 |
| Durability | 15 | 4 | 4 | 5 | 60 | 60 | 75 |
| Ease of installation | 10 | 5 | 4 | 2 | 50 | 40 | 20 |
| Initial cost (CAPEX) | 15 | 3 | 4 | 2 | 45 | 60 | 30 |
| Maintenance cost (OPEX) | 10 | 4 | 4 | 3 | 40 | 40 | 30 |
| Local availability | 5 | 4 | 5 | 4 | 20 | 25 | 20 |
| **Total** | | | | | **420** | **385** | **325** |

Explanations: CAPEX = capital expenditures, OPEX = operating expenses.
Source: own study.

**Table 8.** Pipe specifications

| Specification | Amount | Unit / material |
|---|---|---|
| Flow rate (*Q*) | 0.08818 | $m^3 \cdot s^{-1}$ |
| Pipe length (*L*) | 101 | m |
| Pipe diameter (*D*) | 6 | inch |
| Friction factor (*f*) | 0.02 | HDPE |
| Gravity (*g*) | 9.81 | $m \cdot s^{-2}$ |

Explanations: 6 inches = 0.1524 m, HDPE as in Tab. 7.
Source: own study.

a main pipe diameter of 160 mm (6 inches) and a flow velocity of 4.78 $m \cdot s^{-1}$ from the previous calculation. These results indicate that the selected pipe size and material can accommodate the expected landfill gas flow while maintaining acceptable pressure losses, ensuring efficient and safe system operation. The values of the fittings are presented in Table 9.

**Table 9.** Loss coefficients (*K*) for each type of fitting

| Fitting | *K*-value (per fitting) | Fitting used | *K*-total |
|---|---|---|---|
| Bend 90° | 0.9–1.5 (use 1.0) | 58 | 58 |
| Bend 90° OD 90 mm | 0.8 | 2 | 1.6 |
| Bend 45° | 0.4–0.6 (use 0.5) | 17 | 8.5 |
| Tee | 0.6–0.9 (use 0.6) | 45 | 27 |
| Gate valve 100 mm | 0.15–0.2 (use 0.2) | 2 | 0.4 |
| Gate valve 80 mm | 0.2 | 2 | 0.4 |
| Stub flange + backing ring | ≈0.1–0.2 (use 0.15) | 4 | 0.6 |
| Gasket rubber 150 and 80 mm | ≈0.05 | 4 and 2 | 0.3 |
| ***K*-total** | | | **96.8** |

Explanations: OD as in Fig. 4.
Source: own study.

Based on the total loss coefficient (*K*-total), the minor head loss from all fittings was calculated to be approximately 112.8 m, while the major head loss obtained previously was about 15,400 mm. Therefore, the total head loss of the system, combining both major and minor losses, is estimated to be around 128,200 mm. This significant contribution from minor losses highlights the importance of considering fittings and accessories in the design process, as they can greatly influence overall system performance and pressure requirements.

The compressor power requirement for extracting methane ($CH_4$) from the landfill system was estimated based on the calculated parameters. With a gas flow rate of 0.08818 $m^3 \cdot s^{-1}$ (317.44 $m^3 \cdot h^{-1}$) and a total head loss of approximately 128.2 m, the theoretical compressor power was calculated to be about 132.34 W (0.132 kW). This relatively low power demand indicates that the system can operate efficiently with minimal energy consumption, making it suitable for integration into landfill gas recovery projects without significant operational costs.

In practice, the calculated value represents only the minimum theoretical power. Blower systems typically experience additional losses such as suction resistance, piping, and moisture, which means the actual requirement is higher. For safety, systems are often overdesigned by a factor of 5–10. The recommended compressor specifications are presented in Table 10.

**Table 10.** Compressor specifications

| Specification ideal | Value / type |
|---|---|
| Capacity | ≥320 $m^3 \cdot h^{-1}$ |
| Vacuum pressure (inlet) | −10,000 Pa |
| Outlet pressure | 30,000–50,000 Pa |
| Electricity power | 1–2.2 kW |
| Blower | side channel / rotary vane |

Source: own study.

Based on these considerations, the minimum required compressor should have a capacity of at least 320 $m^3 \cdot h^{-1}$, a vacuum pressure range of −10,000 to −20,000 Pa, and a power rating of 1–2.2 kW. The most suitable types are side channel blowers or rotary vane compressors. A compressor with 4–5 kW capacity would be oversized and inefficient for this system.

The methane capture efficiency was calculated using Equation (8), as the ratio between the volume of methane captured and the potential volume of methane produced from the landfill, expressed as a percentage.

Based on the flow rate and operational data, the captured methane volume was approximately 2,061,085 $m^3$, resulting in an efficiency of about 74.98%. This indicates that the system performs well in recovering methane, though there is still room for improvement through enhanced collection infrastructure and operational practices to minimise losses.

Using the LandGEM equation (IPCC, 2006; Scheutz and Kjeldsen, 2019), the potential methane production after six years was estimated at approximately 2,780,763.76 $m^3 \cdot y^{-1}$. Compared to this potential, the actual captured volume – calculated from a gas flow rate of 0.08818 $m^3 \cdot s^{-1}$ (equivalent to 7,529 $m^3 \cdot d^{-1}$) – reflects an efficiency within the expected range for modern systems. According to the (US EPA, 2022) and (Stege, 2007), landfill gas collection systems typically achieve from 60% to 85% efficiency, with an average of 75%, depending on landfill conditions, system design, and maintenance.

## CONCLUSIONS

The core technology configuration that is technically feasible for implementation at the Jeruklegi controlled landfill includes vertical extraction wells (6 inches = 0.1524 m); effective depth (5–10 m) connected to high-density polyethylene (HDPE) lateral and header pipelines (PE100 grade, butt-fusion/electrofusion joints for leak-tightness).

The gas collection system should employ a low negative-pressure vacuum blower (typical 1,000–3,000 Pa at the wellhead) with adequate turndown capability.

Condensate management requires drip legs or traps at low points and a knockout pot to avoid slugging and suction loss. Downstream utilisation options include a closed flare (minimum combustion efficiency ≥90%) and/or landfill gas (LFG)-to-energy units (genset or microturbine) where gas quality and flow are stable. Proper monitoring and control systems (flow meter, differential pressure, temperature, $CH_4$–$CO_2$–$O_2$ composition, and surface leak inspections) are essential for safe and efficient operations.

The efficiency of the gas collection system is influenced by multiple factors. Geometric parameters such as well spacing, effective depth, and grid layout determine coverage; with an area of 63,000 $m^2$, a well spacing of 36–37 m, and ~48 wells provide adequate coverage for a 5,000–10,000 mm waste lift. Hydraulic design is critical: safe header velocity is 3–5 $m \cdot s^{-1}$ to minimise turbulence and condensate entrainment, with the reference value of 4 $m \cdot s^{-1}$. The Moody friction factor for HDPE pipes at Reynolds numbers of $10^5$–$10^6$ is 0.017, which was adopted in the design. Major head losses are greatly reduced when increasing header diameter (e.g., from 2 to 3–4 inches (from 50 to 100 mm)), which stabilises suction across the wellfield. Additional factors include the quality of cover materials, landfill moisture balance, and ongoing operation and maintenance (O&M) practice, such as leak testing, vacuum tuning at wellheads, condensate removal, and system balancing. Gas quality (50–60% $CH_4$) directly affects energy potential, while trace components ($H_2S$ or non-methane volatile organic compunds (NMVOC)) must be monitored for equipment protection.

From the methane generation model (LandGEM), using inputs of waste mass disposed in year *i* (*Ri*) – 61,560 $Mg \cdot y^{-1}$, potential methane generation capacity (*Lo*) – 170 $m \cdot Mg^{-1}$, and a decay constant of $0.05 \cdot y^{-1}$ over a 6-year period, the peak methane generation was estimated at 0.087 $m^3 \cdot s^{-1}$, equivalent to 314 $m^3 \cdot h^{-1}$.

Correspondingly, the total landfill gas flow rate (with approximately 55% $CH_4$) is 0.158 $m^3 \cdot s^{-1}$, or about 570 $m^3 \cdot h^{-1}$. These values served as the basis for sizing the pipe manifold, header, condensate knockout, and blower.

The optimal pipe diameter to maintain gas velocity within 3–5 $m \cdot s^{-1}$ was calculated as 6.5 inches (about 166.5 mm), and a practical field solution is to use a 6-inch HDPE pipe (approximately 152 mm internal diameter).

Hydraulic analysis showed a major head loss of ±15,400 mm in a 101,000 mm long 6-inch pipe, with additional minor losses from fittings and accessories of ±112,800 mm, resulting in a total system head loss of ±128,200 mm. The theoretical compressor power required to overcome this head loss at a flow rate of 0.08818 $m^3 \cdot s^{-1}$ (methane density 0.716 $kg \cdot m^{-3}$) was calculated as 0.13 kW. However, after accounting for system efficiency and safety factors, a practical compressor capacity of 1–2.2 kW with suction pressure from −10,000 to −20,000 Pa is recommended.

The actual methane volume captured, based on annual operation, was estimated at ±2,061,085 $m^3 \cdot y^{-1}$, compared to the theoretical potential of ±2,780,763.76 $m^3 \cdot y^{-1}$. This results in a capture efficiency of approximately 75%, which aligns well with the United States Environmental Protection Agency (US EPA, 2024) benchmarks (60–85%, with an average around 75%). For an active landfill area of ~63,000 $m^2$, a total of 48 vertical extraction wells with a ~36,000 mm grid spacing is required for adequate coverage.

Overall, the Jeruklegi landfill gas collection system design demonstrates that a technically feasible, efficient, and scalable configuration can be achieved, targeting methane capture efficiencies of 70–85% under good operational practices and enabling both compliance through flaring and potential energy recovery through LFG-to-energy applications.

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## CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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