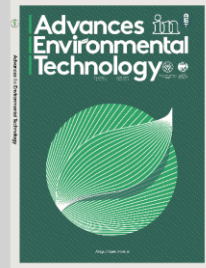




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# Assessment of landfill gas production in Saveh City using the LandGEM model: A comprehensive analysis

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## ABSTRACT

This study assesses the landfill gas (LFG) production potential in the city of Saveh, Iran, utilizing the Landfill Gas Emissions Model (LandGEM) to estimate methane and other emissions based on the area's waste characteristics, environmental factors, and projected waste volumes. Saveh's landfill is expected to see increasing waste production, driven by urban population growth and economic expansion, with waste quantities rising from 150 tons daily in 2014 to over 175 tons by 2030. Given the semi-arid climate, methane generation is influenced by limited moisture, with waste moisture content typically between 20 and 30%. Methane and overall landfill gas emissions are projected to peak by the year 2035, aligning with the landfill's maximum waste capacity. Environmental impacts associated with methane's high global warming potential, along with health risks from non-methane organic compounds (NMOCs) such as benzene, underscore the need for emission control measures. Recommended strategies include methane capture for energy recovery, enhanced waste diversion programs to reduce organic input, leachate recirculation to optimize moisture, and NMOC treatment to mitigate air quality concerns. This analysis provides a framework for managing Saveh's landfill emissions effectively, contributing to climate and health protection goals. Additionally, sensitivity analyses highlight how parameter adjustments, such as increased moisture or waste composition changes, could enhance methane recovery. The study demonstrates the importance of localized data in refining LFG models like LandGEM for accurate emission forecasting in specific environments.

## 1. Introduction

The disposal of municipal solid waste (MSW), primarily through landfilling, contributes to the increasing discharge of organic pollutants into the environment and water resources. This poses a

pressing global environmental challenge, especially in Iran, where landfilling remains the main waste management strategy [1,2]. Reducing the global climate impacts of MSW landfilling requires a comprehensive understanding of the factors that influence gas production and subsequent emissions

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[3,4]. Gas generation in MSW landfills is primarily a biologically mediated process, in which microorganisms decompose organic materials under anaerobic conditions, forming biogas methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) [5-7]. Factors such as moisture content, pH, and temperature of the waste mass significantly affect the rate of gas generation [8,9]. Microbial activity, which thrives in higher moisture conditions, speeds up the decomposition process significantly, as demonstrated in studies where optimal moisture content significantly boosted microbial activity in biosolid composting environments [10]. Similarly, optimal pH and temperature conditions further support the breakdown of organic matter, leading to increased  $\text{CH}_4$  generation, as observed in studies that examined the effects of these factors on microbial activity during organic material decomposition [11,12]. In regions like arid climates with low moisture content, studies have shown that  $\text{CH}_4$  generation is reduced due to decreased microbial activity [10,13]. This makes regional climate a critical factor in assessing the overall gas generation potential of landfills. Additionally, the waste composition itself varies significantly based on local consumption patterns and economic factors. In regions with higher organic waste content, such as food and green waste,  $\text{CH}_4$  generation tends to be higher, as these materials decompose more rapidly under anaerobic conditions [11,14]. Understanding the unique characteristics of a region's waste profile is thus critical for accurate gas generation estimation. Localized data helps refine models like LandGEM to improve their accuracy for specific regions [12,15]. Evaluating  $\text{CH}_4$  gas emissions from landfills has garnered significant interest, with the LandGEM model being extensively used for this task [15]. Landfill gas (LFG) generation is influenced by more than just environmental factors such as climate and waste composition. Operational practices also significantly impact LFG generation. Practices such as compaction, cover materials, and landfill design affect the rate of gas generation and collection efficiency [16]. Aeration has become a widely adopted method to enhance waste degradation, as it promotes aerobic processes and  $\text{CH}_4$  oxidation, which significantly reduces  $\text{CH}_4$  emissions [17-19]. Aeration accelerates microbial activity, enabling

methanotrophic bacteria to oxidize methane into  $\text{CO}_2$ , a reaction that helps mitigate the greenhouse impact of  $\text{CH}_4$  emissions [20]. Studies have shown that methane oxidation reactions are more advantageous during landfill aeration, leading to a more efficient breakdown of organic materials [17]. Aeration promotes a more balanced and uniform microbial community, which is essential for ongoing methane oxidation. The availability of oxygen enables methanotrophic bacteria to flourish, resulting in increased  $\text{CH}_4$  removal rates [21]. Anaerobic conditions usually prevail in the deeper layers of landfills, causing higher  $\text{CH}_4$  and  $\text{CO}_2$  production compared to aerobic conditions, which are more common in the upper layers or areas with better oxygen access [22,23]. However, managing aeration effectively is challenging due to waste heterogeneity and technical complexities at landfill sites. In many cases, both anaerobic and aerobic reactions occur simultaneously in different sections of the landfill, leading to variations in gas production rates across the site [24]. Therefore, operational practices like aeration must be optimized to maximize gas recovery and reduce emissions [25]. For instance, landfill sites with well-distributed air injection systems and controlled oxygen levels have been shown to have higher methane oxidation efficiency [26].

## 2. Materials and methods

### 2.1. Description of the study area

Saveh has a population of 220,762 as of 2016 (112,742 male and 108,020 female). It has been experiencing steady population growth over the years, with a 10.12% increase since 2011 and a 22.29% growth since 2006. This growing population has led to an increase in MSW generation, which directly impacts landfill operations. The physical composition of Saveh's waste is varied and influenced by the city's consumption patterns. Table 1 summarizes the average physical composition of the waste, with 61% being biodegradable materials, including organic waste, while the remaining 39% is composed of materials such as plastics, metals, and glass. Additionally, Table 2 provides an analysis of the particle size distribution in the waste. The percentage of particles across different dimensions ranges

significantly. The presence of larger particles (above 12.7 cm) suggests a need for optimization in waste handling and separation techniques. Due to the unacceptable range in the second measurement from the winter of 2011, this value was removed from the calculations, and the average was calculated based on the previous three values. As shown in Table 3, Saveh is projected to have a population of 239,234 by 2024 and 258,908 by 2030, with corresponding increases in daily waste generation from 150 tons in 2014 to 162.5 tons in 2024 and 175.3 tons in 2030. The annual waste generation is expected to rise from 54,750 tons in 2014 to 63,045 tons by 2030, reflecting an overall increase in waste production. The amount of waste produced will also continue to increase in line with the trend observed in other metropolitan cities of Iran, such as Isfahan and Tehran. The generation of waste per capita in the year 2014 stood at 0.83 kg/c/d, but with the trend in urbanization and consumption, this might increase to 0.88 kg/day in

2024 and reach up to 0.92 kg/day by the year 2030. The estimated yearly cost of collection, transportation, and burial of these wastes is 70 billion Iranian Rial (approximately 1.65 million USD), which further means that for every kilogram of waste, there is a cost of roughly 130 Iranian Rial to the municipality a significant burden. A large-scale separation program does not exist; thus, a significant fraction of the waste goes directly to landfills, consequently enhancing both environmental and economic costs. The chemical composition of the biodegradable waste of Saveh's municipal waste is given in Table 4. It shows that its average moisture content is 52.3%, and its chemical constituent elements are carbon, hydrogen, oxygen, nitrogen, sulfur, and ash. The C/N ratio, computed at 21.14, suggests that this organic waste produces gases. The detailed percentages of those elements are shown in Table 5, indicating that carbon constitutes 21.3%, and oxygen comprises 66.5% of the whole composition.

**Table 1.** Physical composition of waste in Saveh.

| Season      | Organic Waste (%) | Paper & Cardboard (%) | Plastics (%) | Textiles (%) | Metals (%) | Glass (%) | Rubber (%) | Wood (%) | Average Density (kg/m <sup>3</sup> ) |
|-------------|-------------------|-----------------------|--------------|--------------|------------|-----------|------------|----------|--------------------------------------|
| Fall 2010   | 61.000            | 15.28                 | 8.800        | 4.00         | 1.800      | 4.28      | 4.72       | 0.12     | 320                                  |
| Winter 2011 | 75.050            | 10.08                 | 7.700        | 3.00         | 0.800      | 1.40      | 1.62       | 0.20     |                                      |
| Spring 2011 | 66.850            | 13.15                 | 8.100        | 3.50         | 1.300      | 3.20      | 3.05       | 0.12     |                                      |
| Summer 2011 | 69.200            | 12.25                 | 8.500        | 3.70         | 1.400      | 2.50      | 3.25       | 0.22     |                                      |
| Average     | 68.025            | 12.68                 | 8.300        | 3.50         | 1.300      | 2.84      | 3.17       | 0.16     |                                      |

**Table 2.** Particle size distribution in Saveh's waste

| Sampling Stage |             | % of particles | % of particles | % of particles |
|----------------|-------------|----------------|----------------|----------------|
| Stage 1:       | First Time  | 13.10          | 65.00          | 21.90          |
| Fall 2010      | Second Time | 9.80           | 50.98          | 39.20          |
| Stage 2:       | First Time  | 15.53          | 50.48          | 33.98          |
| Winter 2011    | Second Time | 27.77          | 27.79          | 44.44          |
| Stage 3:       | First Time  | 10.20          | 62.22          | 22.40          |
| Spring 2011    | Second Time | 8.20           | 60.74          | 30.60          |
| Stage 4:       | First Time  | 9.20           | 61.96          | 28.20          |
| Summer 2011    | Second Time | 8.80           | 64.50          | 33.30          |
| Average        |             | 12.81          | 55.48          | 31.69          |

The semi-arid nature of Saveh plays a unique role in influencing the dynamics of its MSW landfill. With temperatures rising above 40°C during the summer and dropping as low as -14°C in the winter, these extremes significantly impact microbial activity within the landfill. Higher temperatures accelerate

the decomposition of organic materials during the summer months, which increases CH<sub>4</sub> generation rates. However, the low annual precipitation, around 206 mm, keeps moisture levels below the minimum threshold for continuous anaerobic decomposition.

The average landfill moisture content, estimated at 20-30%, falls well short of the ideal range of 40-60% needed for optimal CH<sub>4</sub> production. Alongside low precipitation, Saveh experiences high solar radiation, with UV indices peaking at eight during the summer.

This accelerates surface moisture evaporation, further reducing microbial activity during the dry

months. In contrast, colder winter temperatures limit microbial activity, leading to a reduction in gas generation rates. The energy content of Saveh's waste, essential for LFG assessments, varies based on moisture levels. As shown in Table 6, the calorific value is calculated under three conditions: with moisture, without moisture, and without moisture and ash.

**Table 3.** Population and waste generation trends in Saveh (2006-2030)

| Year  | Population | Daily Waste Generation (tons/day) | Annual Waste Generation (tons/year) | Per Capita Waste Generation (kg/person/day) |
|-------|------------|-----------------------------------|-------------------------------------|---------------------------------------------|
| 2006  | 180,680    | 127.81                            | 46650.88                            | 0.70                                        |
| 2011  | 200,587    | 138.46                            | 50538.46                            | 0.76                                        |
| 2016  | 220,762    | 150.00                            | 54750.00                            | 0.83                                        |
| 2024* | 239,234    | 162.50                            | 59312.50                            | 0.88                                        |
| 2030* | 258,908    | 175.30                            | 63045.00                            | 0.92                                        |

\*2024 and 2030 are predicted values based on historical trends.

**Table 4.** Chemical analysis of biodegradable materials in Saveh

| pH   | C/N Ratio | Elements (Kg) |       |       |       |       |       | Average Moisture (%) |
|------|-----------|---------------|-------|-------|-------|-------|-------|----------------------|
|      |           | Ash (%)       | S (%) | N (%) | O (%) | H (%) | C (%) |                      |
| 6.80 | 21.14     | 2.02          | 0.11  | 0.85  | 10.43 | 1.65  | 18.20 | 52.30                |

**Table 5.** Percentage of components from the chemical analysis of biodegradable materials

| Component | % of Total Mass (Including Moisture) | % of Total Mass (Excluding Moisture)            |
|-----------|--------------------------------------|-------------------------------------------------|
| Carbon    | 21.30                                | 18.20                                           |
| Hydrogen  | 8.72                                 | $2 \times \frac{52.30}{18.00} + 1.65 = 7.46$    |
| Oxygen    | 66.50                                | $16 \times \frac{52.30}{18.00} + 10.43 = 56.92$ |
| Nitrogen  | 0.99                                 | 0.85                                            |
| Sulfur    | 0.12                                 | 0.11                                            |
| Ash       | 2.37                                 | 2.02                                            |
| Total     | 100.00                               | 85.56                                           |

**Table 6.** Calorific value of waste in Saveh (in kJ/kg).

| Condition                        | Calorific Value (kJ/kg) |
|----------------------------------|-------------------------|
| With Moisture                    | 7,742.50                |
| Without Moisture                 | 19,969.30               |
| Without Moisture and Without Ash | 21,200.65               |

The corresponding values are 7,742.5 kJ/kg, 19,969.63 kJ/kg, and 21,200.65 kJ/kg, respectively. These figures indicate the potential for energy recovery from waste through LFG processes.

The landfill's operational challenges are compounded by the city's relatively low wind speeds, which average around 10-20 km/h, and the lack of effective gas collection systems. This creates a scenario where much of the CH<sub>4</sub> generated escapes into the atmosphere rather than being recovered for energy purposes.

Furthermore, the average air pressure of 1010 mb also influences gas dispersion, affecting how CH<sub>4</sub> is released from the landfill surface.

## 2.2. Data Sources

The data for this study were obtained from multiple sources. One key source was the comprehensive waste management plan for the city of Saveh, which provided detailed insights into the physical and chemical composition of waste, waste generation trends, and landfill operations. Additionally, meteorological data from local weather stations were utilized to evaluate environmental factors affecting LFG production, including temperature, precipitation, and wind speeds. Seasonal waste composition surveys were

also conducted to analyze the types and quantities of waste being deposited in the landfill.

### 2.3. Mathematical Equations for Gas Generation in Landfills

LFG generation is primarily governed by first-order decay kinetics, which model how organic waste decomposes over time in anaerobic conditions to produce CH<sub>4</sub> and CO<sub>2</sub>. These gases are released as microorganisms break down the waste.

The first-order decay equation is used to estimate the rate of CH<sub>4</sub> production over time, and is expressed as follows:

$$Q_{CH_4}(t) = L_0 \cdot W \cdot e^{-kt} \quad (1)$$

Here,  $Q$  denotes the CH<sub>4</sub> volume generated at time  $t$ ,  $W$  is the mass of waste, and  $L_0$  is the potential methane-generation capacity. The decay constant,  $k$  (yr<sup>-1</sup>), describes the rate at which CH<sub>4</sub> generation declines over time and depends on moisture content, nutrient availability, pH, temperature, and site-specific landfill conditions.

### 2.4. Parameters Affecting the Decay Constant

In Saveh's landfill, several key factors influence the decay constant. One of these is moisture content, which in this region averages between 20 and 30%. Since optimal CH<sub>4</sub> generation occurs at moisture levels between 40-60%, the relatively lower moisture content in Saveh results in suboptimal CH<sub>4</sub> production. This directly affects the  $k$  value, as higher moisture levels enhance microbial activity and accelerate decomposition. Temperature is another crucial factor, given Saveh's semi-arid climate, where summer temperatures exceed 40°C and winter temperatures drop to -14°C. These fluctuations create variable conditions for microbial activity, with higher temperatures accelerating decomposition and increasing  $k$ , while colder temperatures slow down microbial processes and gas production. Additionally, the composition of organic waste plays a significant role, as 61% of the waste in Saveh is biodegradable, primarily consisting of organic material. This enhances CH<sub>4</sub> production, but variations in waste composition, including the presence of plastics, metals, and other non-biodegradable materials, can impact the total potential CH<sub>4</sub> yield.

The coefficients of first-order models, such as the Southwest Asia and North Africa (SWANA) models, are generally found to overestimate LFG emissions under stable and ideal conditions, as documented in several studies. An expanded model improves upon the initial first-order approach by incorporating more detailed parameters, including climate conditions, waste composition, and landfill management practices, as expressed below:

$$Q_{LFG} = \sum_{i=1}^n \sum_{j=0.1}^1 2kL_0 \left[ \frac{M_i}{10} \right] (e^{-kt_{ij}})(MCF)(F) \quad (2)$$

In this equation,  $Q_{LFG}$  represents the maximum estimated gas production rate of the landfill, while  $n$  denotes the annual time increase and the time gap between the landfill's start year and the analyzed year. The mass of waste deposited in the  $i$ -th year is expressed as  $M_i$ , and the equation accounts for part  $j$  of the waste, where  $t_{ij}$  indicates its age. The CH<sub>4</sub> correction factor,  $MCF$ , adjusts estimates based on local conditions, such as climate and landfill management practices. Additionally,  $F$  serves as an adjustment factor to account for CH<sub>4</sub> loss due to landfill fires, which could influence total gas emissions [27-29].

### 2.5. The Role of the LandGEM Program in Estimation

The LFG Emissions Model (LandGEM), developed by the U.S. Environmental Protection Agency (EPA), is a widely used tool for estimating the amount of LFG produced from MSW landfills. Using the first-order decay equation, LandGEM estimates CH<sub>4</sub> and CO<sub>2</sub> generation over time.

In the context of Saveh, several key inputs are critical for the model. One important factor is waste composition, as 61% of Saveh's waste is biodegradable. This plays a crucial role in estimating potential CH<sub>4</sub> generation. Another essential input is the annual waste acceptance rate, which considers the yearly increase in waste generation, projected to reach 175.3 tons per day by 2030. Additionally, decay rates are significant, as LandGEM allows for the input of local decay rates ( $k$ ), which vary depending on climate and environmental conditions.

Using these inputs, LandGEM calculates total CH<sub>4</sub> generation over the landfill's lifetime, with outputs including the estimated total volume of CH<sub>4</sub> and

CO<sub>2</sub>, peak CH<sub>4</sub> production years, and total potential for energy recovery through LFG collection.

## 2.6. Example Calculation for Saveh

To provide a more concrete understanding of gas generation in Saveh's landfill, consider an example where the annual waste generation in 2024 is projected to be 162.5 tons/day, with 61% of this waste being organic. Using the first-order decay model, the gas generation rate can be estimated, allowing us to predict CH<sub>4</sub> yields for the next several decades.

$$Q_{CH_4}(t) = 100 \text{ tons} \times 0.06 \frac{m^3}{kg} \times e^{-0.02 \times t} \quad (3)$$

Where the potential gas emission rate is assumed to be 0.06 m<sup>3</sup>/kg for organic waste, and  $k = 0.02 \text{ year}^{-1}$  is based on Saveh's semi-arid climate. This equation helps estimate the CH<sub>4</sub> yield for any given year, enabling accurate forecasting for gas recovery operations.

## 2.7. Proposed Improvements and Sensitivity Analysis

The proposed improvements to the Saveh landfill are aimed at optimizing CH<sub>4</sub> recovery while reducing environmental risks associated with current waste management practices. The application of the first-order decay model in Saveh's landfill has the potential to significantly improve LFG recovery efficiency by factoring in local climate conditions, waste composition, and other key environmental parameters.

A sensitivity analysis can also be conducted to assess how variations in parameters like moisture content, organic waste percentage, and landfill operational practices influence CH<sub>4</sub> production. For example, if Saveh's landfill moisture content increases from 30% to 40%, CH<sub>4</sub> generation could increase by as much as 25%, significantly enhancing gas recovery potential.

## 2.8. LandGEM Model Setup

The LandGEM (LFG Emissions Model, U.S. EPA version 3.02) was employed to estimate the potential gas generation from Saveh's municipal landfill. LandGEM applies a first-order decay equation to simulate CH<sub>4</sub> and CO<sub>2</sub> emissions from MSW landfills. The model setup was adjusted and partially calibrated to reflect the local

environmental and waste management conditions in Saveh.

### 2.8.1. Model Parameters

The decay rate ( $k$ ) used in the model was set to  $k = 0.02 \text{ year}^{-1}$ , reflecting the semi-arid conditions of Saveh. This value was chosen due to the lower moisture content (20-30%) in the landfill. For CH<sub>4</sub> generation potential ( $L_0$ ), the estimate was 60 m<sup>3</sup>/ton, based on the high organic content of the waste, which is approximately 61%. To account for inefficiencies in gas collection and variability in landfill management practices, a methane correction factor (MCF) of 0.85 was applied. The organic waste content, which drives CH<sub>4</sub> production, was determined to be 61% based on seasonal waste composition studies.

### 2.8.2. Waste Input

The daily waste generation was set at an average of 150 tons per day for the baseline year of 2016, with projected increases to 162.5 tons per day by 2024 and 175.3 tons per day by 2030. The total waste volume was determined by calculating the cumulative waste using historical records and future projections for waste generation.

### 2.8.3. Model Calibration and Validation

To assess the reliability of the model, CH<sub>4</sub> generation rates predicted by LandGEM were compared with empirical estimates from published Iranian studies and default EPA scenarios for similar climatic conditions. The predicted CH<sub>4</sub> yield (54-58 m<sup>3</sup> CH<sub>4</sub> ton<sup>-1</sup>) fell within the expected range, confirming the suitability of the selected  $k$  and  $L_0$  parameters. Therefore, the model was considered adequately calibrated for the Saveh landfill context.

### 2.8.4. LandGEM Outputs

The model provided estimates for total CH<sub>4</sub> production, annual CH<sub>4</sub> emissions, and the peak production year for gas extraction. The results were used to evaluate the gas recovery potential of the landfill under current conditions.

## 2.9. Chemical and Physical Analysis of Waste

The physical composition of the waste was analyzed through seasonal surveys, which categorized the waste into biodegradable (61%)

and non-biodegradable fractions. The size distribution of the waste particles was also recorded, with a significant portion of the waste consisting of particles larger than 12.7 cm, which impacts decomposition rates. The chemical analysis of the biodegradable fraction was conducted to estimate the calorific value of the waste and the potential for CH<sub>4</sub> generation.

The moisture content of the waste averaged 52.3%, with seasonal variations influencing decomposition rates. The carbon-to-nitrogen (C/N) ratio was measured at 21.14, which falls within the optimal range of 20-30 for maximizing CH<sub>4</sub> production [30]. Ratios below 15 can cause ammonia inhibition, while values above 35 may lead to nutrient deficiency and process instability [31]. The elemental composition of the waste was analyzed to estimate gas generation potential, with measured values of carbon (21.3%), hydrogen (8.72%), oxygen (66.5%), nitrogen (0.99%), and sulfur (0.12%).

## 2.10. Calorific Value Determination

The calorific value of Saveh's waste was calculated in three conditions: with moisture, without moisture, and without moisture and ash. The formula used for calculating the calorific value was based on the Dulong equation:

$$\text{Calorific Value} \left( \frac{\text{Btu}}{\text{lb}} \right) = 145C + 610 \left( H - \frac{1}{8}O \right) + 40S + 10N \quad (4)$$

In this analysis, C, H, O, S, and N represent the percentages of carbon, hydrogen, oxygen, sulfur, and nitrogen in the waste, respectively. The calorific value of the waste was calculated to be 7,742.5 kJ/kg when measured with moisture, 19,969.63 kJ/kg without moisture, and 21,200.65 kJ/kg when both moisture and ash are excluded. These values were subsequently used to estimate the potential energy recovery from the waste if it were converted to biogas.

## 2.11. Sensitivity Analysis

A quantitative sensitivity analysis was conducted to evaluate how changes in key parameters, including moisture content, organic waste fraction, and decay rate (*k*), affect CH<sub>4</sub> generation. The analysis aimed to identify the most influential factors controlling LFG yield in Saveh's landfill. Based on the

analysis of similar study areas to Saveh, these literature-derived sensitivity ranges were used as benchmarks to interpret the sensitivity simulations, placing the quantitative results in a broader regional and methodological context (Table 7).

### 2.11.1. Moisture Content

The baseline moisture content of 30% was varied between 20% and 40% to simulate drier and wetter conditions. Results indicate that increasing the moisture content to 40% (achievable through leachate recirculation) raised CH<sub>4</sub> generation by approximately 22%, whereas reducing it to 20% lowered CH<sub>4</sub> production by 15%. This confirms the strong dependency of microbial decomposition activity on moisture availability.

### 2.11.2. Organic Fraction

Varying the organic fraction of the waste from 50% to 65% demonstrated a significant effect on gas generation. Increasing the organic portion from 61% (baseline) to 65% enhanced CH<sub>4</sub> yield by about 11%, while reducing it to 50% led to an 18% decline. These findings highlight the impact of waste composition and the potential benefits of composting and recycling programs in managing organic input.

### 2.11.3. Decay Rate (*k*)

Sensitivity analysis on the decay rate was performed for values between 0.03 and 0.07 year<sup>-1</sup>, representing different environmental conditions. An increase of *k* from 0.02 to 0.05 year<sup>-1</sup> resulted in a 35% rise in CH<sub>4</sub> production, while further increasing to 0.07 year<sup>-1</sup> yielded up to 50% more CH<sub>4</sub>. This demonstrates that small improvements in landfill management and moisture control could significantly increase gas generation.

## 3. Results and discussion

To estimate CH<sub>4</sub> generation and LFG production for Saveh's municipal waste, the LandGEM model was used due to its effectiveness in assessing gas emissions from waste decomposition. This model, based on first-order decay kinetics, is well-suited for predicting gas production over time in anaerobic landfill conditions.

**Table 7.** Summary of sensitivity analysis results for the Saveh Landfill.

| Key Parameter           | Key Finding                                                                                                                                          | Reference |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Moisture content        | Raising the moisture content from 25% to 40% led to approximately a 20-25% increase in CH <sub>4</sub> production.                                   | [8]       |
| Organic Fraction        | Varying the organic fraction from 50% to 65% produced about a 10-15% increase in CH <sub>4</sub> output.                                             | [15]      |
| Decay Rate ( <i>k</i> ) | Increasing the decay constant ( <i>k</i> ) from 0.02 to 0.07 resulted in a 40-55% rise in CH <sub>4</sub> generation in semi-arid Chinese landfills. | [27]      |

By customizing parameters to align with Saveh's unique climate, waste composition, and projected waste volumes, the model provides more accurate and region-specific results. Simulations offer a detailed projection of CH<sub>4</sub> and other LFG emissions throughout the landfill's operational and post-closure periods, highlighting key emission trends, peak production years, and cumulative gas outputs.

### 3.1. Waste Accumulation and Input Data

The annual waste acceptance and cumulative waste-in-place values presented in Table 8 are fundamental to calculating gas emissions. Based on projected population and economic growth rates, Saveh landfill is expected to accumulate waste consistently over the next 25 years, increasing from 32,631 Mg/year in 2010 to 97,237 Mg/year in 2035. The cumulative waste-in-place by 2035 is estimated to reach 1,620,600 Mg, setting the foundation for gas generation.

### 3.2. CH<sub>4</sub> and LFG Emissions

The model projects annual emissions of CH<sub>4</sub>, CO<sub>2</sub>, and total LFG, reflecting both the decomposition rate and the increasing waste volume over time. Emissions are initially low in the early years but rise significantly as waste accumulation increases and decomposition processes intensify. The peak emission period for Saveh landfill is projected to occur around 2035, with CH<sub>4</sub> emissions reaching their highest levels before gradually declining. This decline occurs as waste decomposition slows post-closure and the remaining organic material becomes limited. (See Figure 1: Annual Emissions of Landfill Gas, CH<sub>4</sub>, CO<sub>2</sub>, and Benzene (Megagrams per Year) in the Methodology section for a visual representation of these trends.)

### 3.3. Key Parameters for Model Setup

The LandGEM model setup for Saveh focused on several critical inputs that influence gas generation rates: the CH<sub>4</sub> generation rate (*k*), CH<sub>4</sub> potential (*L*<sub>0</sub>), NMOC (non-methane organic compounds) concentration, and CH<sub>4</sub> content.

Each parameter was selected based on local data, specific climate considerations, and waste characteristics.

#### 3.3.1. CH<sub>4</sub> Generation Rate (*k*)

For Saveh's semi-arid climate, the decay rate constant was adjusted to reflect moderate moisture levels and microbial activity. A baseline rate of 0.05 year<sup>-1</sup> was chosen, consistent with semi-arid conditions where moisture typically restricts microbial efficiency. As shown in Table 8 (LandGEM model input parameters for Saveh Landfill), sensitivity analysis around this baseline, ranging from 0.03 to 0.07, allowed for a broader understanding of how environmental variations might impact CH<sub>4</sub> generation.

#### 3.3.2. CH<sub>4</sub> Generation Potential (*L*<sub>0</sub>)

The CH<sub>4</sub> generation potential reflects the organic content of the waste and its decomposition characteristics. With approximately 61% organic content in Saveh's municipal waste, the model assumed an *L*<sub>0</sub> value of 170 m<sup>3</sup> per ton of waste, a standard for waste with high organic composition. Adjustments for higher or lower organic fractions, as explored in the sensitivity analysis, can fine-tune this figure for alternative waste compositions.

#### 3.3.3. NMOC Concentration

Non-methane organic compounds contribute to overall landfill emissions and environmental impact. An NMOC concentration of 4,000 parts per million by volume (ppmv) of hexane was used, aligning with standard values observed in

comparable landfills. As shown in Table 9, this figure was maintained constant across scenarios

due to limited data on NMOC variations in Saveh's waste composition.

**Table 8.** LandGEM model input parameters for Saveh Landfill.

| Parameter                                         | Value                           | Unit               |
|---------------------------------------------------|---------------------------------|--------------------|
| Landfill open year                                | 2010                            | year               |
| Landfill closure year (with 80-year limit)        | 2035                            | year               |
| Actual closure year (without limit)               | 2035                            | year               |
| Have the model calculate the closure year?        | Yes                             | -                  |
| Waste design capacity                             | 1,620,600                       | megagrams          |
| CH <sub>4</sub> generation rate, <i>k</i>         | 0.050                           | year <sup>-1</sup> |
| Potential CH <sub>4</sub> generation capacity, L0 | 170                             | m <sup>3</sup> /Mg |
| NMOC concentration                                | 4,000                           | ppmv as hexane     |
| CH <sub>4</sub> content                           | 50                              | % by volume        |
| Gas/pollutant #1                                  | Total landfill gas              | -                  |
| Gas/pollutant #2                                  | Methane                         | -                  |
| Gas/pollutant #3                                  | Carbon dioxide                  | -                  |
| Gas/pollutant #4                                  | Benzene - Co-disposal - HAP/VOC | -                  |

**Table 9.** Primary pollutant parameters for Saveh Landfill.

| Compound           | Concentration (ppmv) | Molecular Weight |
|--------------------|----------------------|------------------|
| Gases              |                      |                  |
| Total landfill gas |                      | 0.00             |
| Methane            |                      | 16.04            |
| Carbon dioxide     |                      | 44.01            |
| NMOC               | 4000                 | 86.18            |

### 3.3.4. CH<sub>4</sub> Content

CH<sub>4</sub> is typically about 50% of total LFG [32]. This percentage is standard in LandGEM applications and was adopted for Saveh to provide realistic CH<sub>4</sub> yield estimates. CH<sub>4</sub> content tends to remain stable unless influenced by highly specific environmental or waste composition changes [33, 34].

### 3.4. Waste Input and Projection Data

The annual waste production rate and waste composition are central to LandGEM's calculations. Baseline waste production for Saveh was set at 150 tons per day (or 54,750 tons per year), with projected annual increases based on the city's population and economic growth rates. By 2030, this figure is expected to rise to 175.3 tons per day, equating to 63,045 tons per year. These projections align with urban growth trends in Saveh and allow for accurate modeling of gas production as waste accumulates in the landfill over the next 25 years. Table 10 provides a basis for visualizing the waste input trends over time, which is central to calculating LFG output. These values represent the

cumulative waste amounts over Saveh's landfill lifespan, setting the basis for the LandGEM calculations that follow. Therefore, for the burial of municipal waste in Saveh County over the next 25 years, a land area of approximately 438 square meters with a depth of about 8 meters and dimensions of around 581 by 581 meters is required.

### 3.5. Model Implementation and Data Processing

With all parameters and waste projections established, the LandGEM model calculates annual and cumulative CH<sub>4</sub> production.

By inputting both the waste acceptance rates and cumulative waste volumes, we simulate CH<sub>4</sub> output for each year. The model then generates results, including estimated annual CH<sub>4</sub> volume, cumulative CH<sub>4</sub> production, and peak production years.

The model outputs are particularly useful for identifying peak production years and estimating the total gas volume over time. Seasonal effects were also incorporated by adjusting the *k* value in the sensitivity analysis, allowing the capture of Saveh's seasonal temperature fluctuations and their impact on gas production.

### 3.6. Visualization of Model Outputs

The results from the LandGEM model are best represented visually to highlight trends in gas production over the landfill's operational and post-operational years, as shown in Figure 1, which illustrates the annual emissions of CH<sub>4</sub>, CO<sub>2</sub>, and benzene throughout the simulation period.

**Table 10.** Annual waste acceptance and cumulative waste-in-place for Saveh Landfill.

| Year | Annual Waste Acceptance (tons) | Cumulative Waste-in-Place (tons) |
|------|--------------------------------|----------------------------------|
| 2010 | 2,831                          | 8,804                            |
| 2011 | 3,915                          | 35,834                           |
| 2012 | 4,579                          | 68,008                           |
| 2013 | 4,384                          | 105,808                          |
| 2014 | 4,968                          | 146,191                          |
| 2015 | 5,552                          | 199,159                          |
| 2016 | 6,950                          | 258,182                          |
| 2017 | 10,120                         | 311,132                          |
| 2018 | 13,305                         | 366,924                          |
| 2019 | 15,888                         | 425,069                          |
| 2020 | 18,473                         | 487,036                          |
| 2021 | 21,057                         | 551,357                          |
| 2022 | 23,641                         | 618,520                          |
| 2023 | 26,820                         | 688,525                          |
| 2024 | 28,810                         | 761,373                          |
| 2025 | 33,978                         | 835,598                          |
| 2026 | 37,978                         | 912,572                          |
| 2027 | 41,141                         | 992,902                          |
| 2028 | 44,904                         | 1,081,192                        |
| 2029 | 48,313                         | 1,168,253                        |
| 2030 | 52,318                         | 1,258,157                        |
| 2031 | 56,858                         | 1,350,902                        |
| 2032 | 61,483                         | 1,446,491                        |
| 2033 | 66,068                         | 1,544,923                        |
| 2034 | 70,652                         | 1,645,197                        |
| 2035 | 75,248                         | 1,750,314                        |

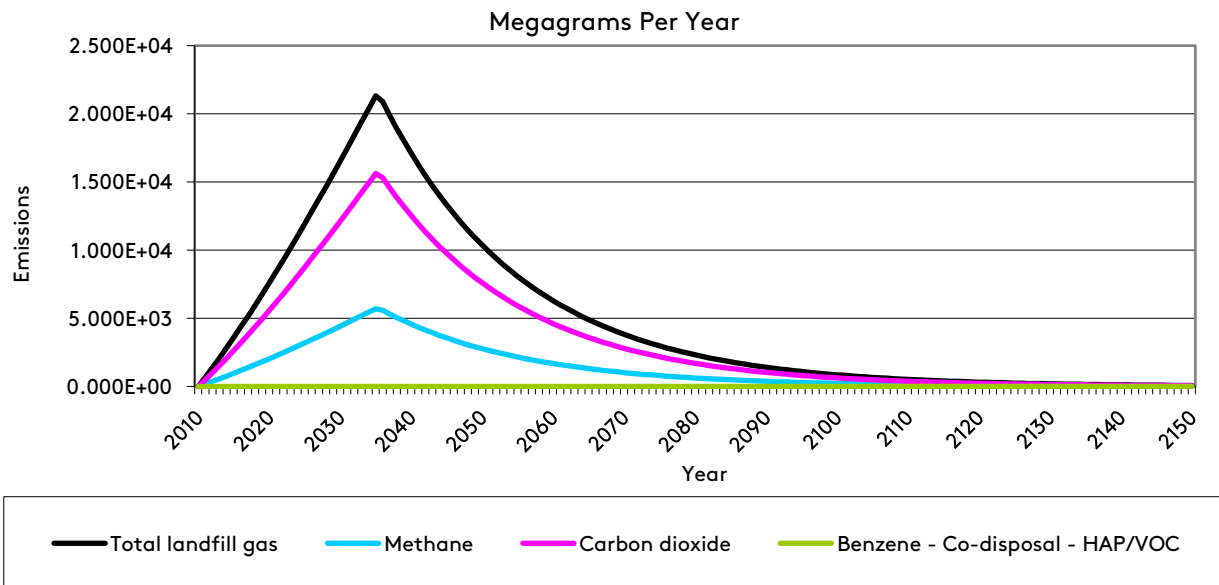
### 3.7. CH<sub>4</sub> and Total LFG Emissions

The LandGEM output chart shows trends in CH<sub>4</sub>, CO<sub>2</sub>, and total LFG production, clearly indicating peak years and subsequent declines.

### 3.8. Annual Emissions Breakdown

To illustrate the proportional contribution of each gas type over time, the annual emissions breakdown chart offers a comparative view. These visual aids help in understanding the temporal behavior of gas emissions, providing insights for potential gas recovery and mitigation strategies. The charts reveal the environmental footprint over time, allowing for discussions on sustainability and emissions management.

To illustrate the proportional contribution of each gas type over time, a comparative view of annual emissions is provided in Figure 2, which presents the breakdown of total landfill gas, CH<sub>4</sub>, CO<sub>2</sub>, and benzene emissions.

**Fig. 1.** Annual emissions of LFG methane, carbon dioxide, and benzene (megagrams per year).

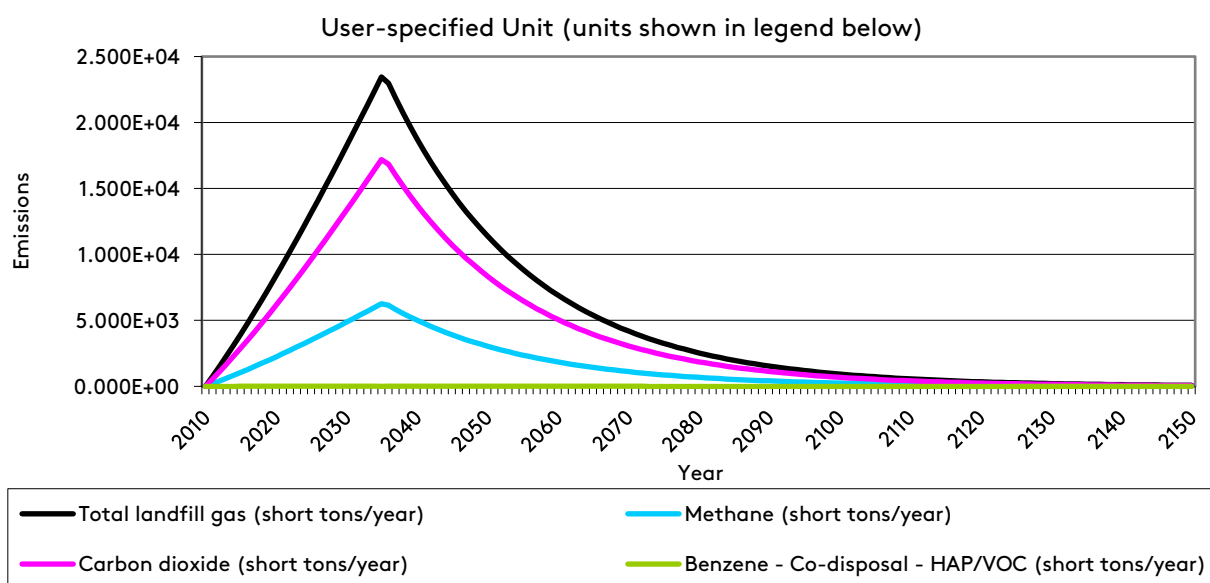


Fig. 2. Annual emissions breakdown of total LFG, CH<sub>4</sub>, CO<sub>2</sub>, and benzene (User-Specified Unit)

#### 4. Conclusion

The LandGEM model projections for the Saveh landfill reveal significant environmental impacts tied to CH<sub>4</sub>, CO<sub>2</sub>, and NMOC emissions, which will peak as waste volumes reach critical levels by 2035. CH<sub>4</sub>, with its high global warming potential, poses a substantial climate risk, while NMOC emissions, including benzene, contribute to air quality concerns and health risks. To mitigate these effects, a multifaceted approach is recommended. First, a CH<sub>4</sub> capture and utilization system could effectively reduce greenhouse gas (GHG) emissions while converting LFG into a renewable energy source for local use. Reducing the organic content of incoming waste through enhanced waste diversion programs, such as composting and recycling, could further limit CH<sub>4</sub> generation, helping to lower future emissions. Additional strategies, including leachate recirculation to optimize moisture and air quality monitoring to manage NMOC levels, would bolster environmental protection efforts. By implementing these recommendations, the Saveh Landfill can significantly minimize its environmental footprint, mitigate health risks, and support sustainable waste management goals. These efforts underscore the importance of proactive landfill management to address GHG emissions and pollution, transforming potential hazards into manageable and even beneficial resources for the community.

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#### Author's contribution

**Ali Mollasalehi:** Conceptualization, Methodology, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing. **Soheil Aghayani:** Formal analysis, Data curation, Software, Investigation, Visualization, Methodology, Writing - review & editing. **Maryam Pazoki:** Supervision, Project administration, Resources, Conceptualization, Formal analysis. **Sajad Borji:** Visualization, Software, Software analysis. All authors have read and approved the final version of the manuscript.

#### Conflict of interest

No potential conflict of interest was reported by the authors.

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