Global NEST Journal, **28** (6), 08569
Available online: 17/07/2026

Greenhouse Gas Emissions from Erbil City Landfill: LandGEM–IPCC Comparison, Energy Recovery Potential, and Policy Implications

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Abstract

Landfill methane (CH_4) emissions represent a significant greenhouse gas (GHG) source globally. This study presents the first simultaneous application and comparison of the LandGEM v3.02 and IPCC Tier 1 models for the Erbil City landfill, Kurdistan Region, Iraq, covering waste acceptance from 2001 to 2031. LandGEM parameters (k = 0.05 $year^{-1}$; L_0 = 170 m^3/Mg) and IPCC parameters (DOC = 0.18; DOC_f = 0.70; MCF = 0.8; F = 0.5) were applied, with energy recovery estimated at 75% CH_4 collection efficiency and 33% electrical conversion efficiency. Peak CH_4 emissions in 2032 are projected at 8.9×10^7 m^3/year (LandGEM) and 1.8×10^8 m^3/year (IPCC), yielding energy potentials of 206 and 416 GWh/year, respectively. The divergence arises because IPCC Tier 1 omits first-order decay kinetics, producing an upper-bound estimate, directly affecting landfill gas collection system sizing and infrastructure decisions. Gross revenue potential ranges from $24–58 million/year, or $10–16 million/year under conservative 40% collection efficiency. All results are model-based projections without field validation. Findings support prioritizing active gas collection infrastructure to convert Erbil's landfill into a renewable energy asset and provide a quantitative basis for regional waste management policy.

Keywords: LandGEM model; IP CC methodology; Methane emissions; Erbil City; Waste management policy.

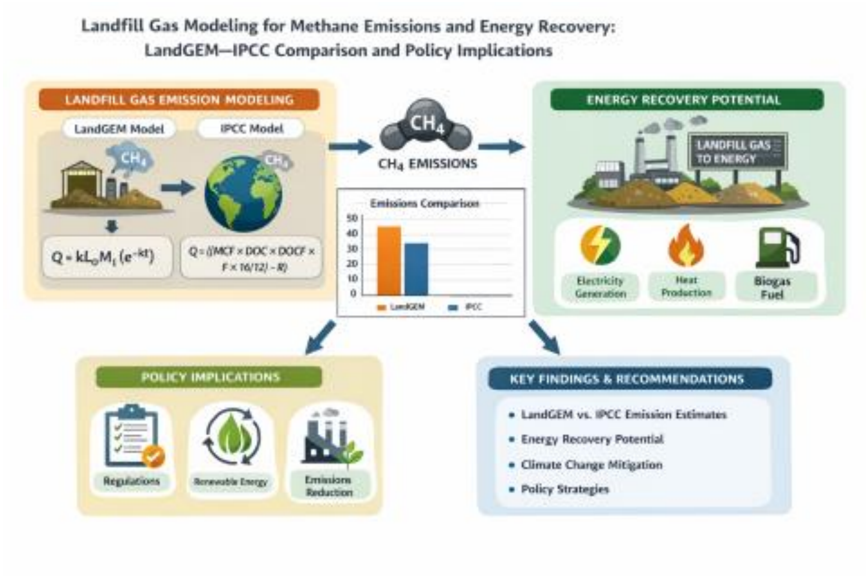
OPEN ACCESS

Received: 08/04/2026,

Accepted: 13/07/2026,

Available online: 17/07/2026

Graphical abstract



1. Introduction

Rapid urbanization and population growth have substantially increased municipal solid waste (MSW) generation globally. Landfilling is still the most common way to get rid of it. Landfills release landfill gas (LFG), mostly methane (CH_4) and carbon dioxide (CO_2), which are major causes of climate change. CH_4 is especially important because it can cause global warming 84 times more than CO_2 over 20 years (Abed & Halos, 2021). Most of the 500–600 Tg of CH_4 emissions that happen each year come from human activities. Landfills are the third-largest human-made source (Bian *et al.*, 2021). Advanced recycling methods like incineration, composting, and anaerobic digestion are helping the waste management industry become more profitable and environmentally friendly. Anaerobic digestion makes organic waste stable, makes renewable energy, and makes organic fertilizers (TOP *et al.*, 2019). It supports decarbonization by reducing GHG emissions and changing fossil-based inputs (Calabrò & Lisi, 2015). Unlike incineration, it reduces air pollution and avoids shortest GHG release. With its multiple benefits, anaerobic digestion is widely known as a key strategy for circular economy development. (Ibrahim *et al.*, 2025).

In Iraq, uncontrolled disposal of mixed MSW in open landfills presents severe environmental hazards, including GHG discharges and leachate contamination. The Erbil landfill site, a Level II anaerobic landfill without gas and leachate control, receives over 2,000 tons of mixed MSW daily (Aziz, 2023). In the absence of gas collection infrastructure, methane escapes uncontrolled into the atmosphere, representing both a significant environmental hazard and an unrealized opportunity for renewable energy recovery (Aziz & Mustafa, 2018).

Two models that attempt to determine the amount of gas originating from landfills are the U.S. EPA LandGEM model and the IPCC default technique. Although both models are extensively applied, their reliance on default parameters rather than site-specific calibrated values introduces uncertainty in emission estimates, particularly when applied to landfills with distinct climatic, compositional, and operational characteristics. The LandGEM model was originally developed for U.S. landfill conditions using default decay rate constants ($k = 0.05$ year^{-1}) and methane generation potential values ($L_0 = 170$ m^3/Mg). The applicability of these default parameters to Iraqi landfill conditions requires justification, as semi-arid climatic conditions, distinct waste composition with high organic fractions, and different operational practices may influence methane generation kinetics. Nevertheless, LandGEM has been applied in comparable arid and developing-country contexts as a conservative engineering design baseline, and its outputs are interpreted here accordingly. Comparative studies in South Africa, Iran, India, and Morocco have demonstrated that collecting gas from landfills can be used to generate energy (Maalouf & El-Fadel, 2020). However, the application of these models to Iraqi landfills remains extremely limited, representing a clear gap in the regional literature (Aziz *et al.*, 2025). As highlighted in Chandrasekaran and Busetty (2022) in their study on municipal solid waste management (MSWM) in the Trichy and Thanjavur regions of India, there was a problem with high organic content, with fractions reaching 14.55% and 11.50%, respectively. The peak CH_4 emission is 1.87×10^7 m^3/year, representing the urgent need for improved waste management solutions. Likewise, Mokhtari *et al.* (2020) examined the Yazd County landfill and discovered that swift population growth led to increased waste production and CH_4 emissions. Their results showed that we need better infrastructure for managing waste right away. This could greatly increase our ability to capture energy. LFG extraction at that site was estimated to generate more than 11 MWh of electricity annually, that could be used to make power. This strategy helped eco-friendly energy recovery methods by making power and lowering dangerous emissions at the same time.

Further investigate by Ramprasad *et al.* (2023) conducted further investigations on the Kanuru landfill site in Vijayawada, India, estimating an annual of 130.8 GWh of electricity and 43.3 Gg of hydrogen fuel alongside renewable hydrogen production form waste through anaerobic digestions. Additionally, Kiehbadroudinezhad *et al.* (2024) demonstrated the significance of landfills for GHG emissions and advocated for more stringent regulations on the use of LFG to produce energy, power, and biomethane. These assertions were also reported by, Oukili and Chhiba (2023). They demonstrated that, in conjunction with flare systems, controlled burning of MSW accelerates the creation of CH_4 and GHG emissions, hence reducing annual GHG emissions. The Weltervenden landfill in South Africa was also examined by Njoku and Edokpayi (2023) Additionally, they examined LFG emissions and how to generate electricity using microturbines and combined heat and power (CHP) systems. Ukraine's substantial energy potential from solid waste landfills was highlighted by Vaskina *et al.* (2024), especially with regard to landfill gas extraction. With 53 million cubic meters of household waste produced in 2021, effective LFG management is critical to reducing emissions and improving energy security. Tong *et al.* (2025) studied CH_4 emissions from 102 major landfills using satellite data and initiate that open dumpsites are underestimated by more than fivefold in global catalogues. They resolved that converting dumps to sanitary landfills and diverting organic waste could reduce releases by up to 80%. Bhar *et al.* (2025) observed Morocco's MSWM and estimated biogas production using LandGEM and IPCC models. Outcomes displayed rising CH_4 emissions, with IPCC predicting higher outputs. By 2045. He and Qu (2026) demonstrated the potential of modular landfill remediation integrated with AI-assisted grid management as a pathway for waste-to-energy optimization in urban settings. Sayed *et al.* (2026) studied tourist-generated waste at Lata Sempeneh, Malaysia, reporting an average of 0.174 kg per capita per day, dominated by food waste (≈64%), with associated carbon emissions of 0.138 kg CO_2-eq per capita per day; diverting half of the food waste through composting could halve emissions, highlighting a practical circular solution for sustainable tourism management.

While previous studies on the Erbil landfill have examined waste characterization (Aziz *et al.*, 2011), recycling potential (Aziz *et al.*, 2023), and gas pipe installation (Aziz & Mustafa, 2018), no prior study has simultaneously applied and compared LandGEM v3.02 and the IPCC Tier 1 default model for this site, nor integrated the comparison with quantified energy recovery potential and gross revenue estimation. This combined methodological framework constitutes the novel contribution of the present work. The study assesses energy recovery capacity and economic viability in addition to emission estimation, providing a comprehensive viewpoint that incorporates environmental, technical, and financial aspects. The results, which emphasize the complementary advantages of emission reduction and renewable energy production, are intended to guide MSWM plans in Erbil City and comparable developing areas.

2. Methodology

2.1. *Study area and data collection*

Erbil Governorate, the capital of the Kurdistan Region, is located in northern Iraq and covers 15,074 km^2 (3.5% of Iraq). as of 2024, Erbil Governorate has around 2,440,560 inhabitants. The Erbil Directorate of Region Service and Environment indicates that the quantity of municipal solid waste collected from Erbil City and conveyed to the Erbil landfill site (Kani Qirzhala) is projected to be around 2,300 tons per day in 2024, as illustrated in **Figure 1**. The landfill, which opened in 2001, is located 15 km from the city center and has a total site area of 37 ha (Aziz *et al.*, 2011).

With an increasing population in Erbil City, the degrading waste levels are increasing at alarming rates, posing greater risks to operating management staff. Dumping activities also include construction and demolition waste, glass, cans, packaging, plastic, glass, cardboard, wood, metals, ceramics, leather, clothes, and batteries (Gardi, 2017).

A tiny portion of recyclable goods, like plastic, glass, and metals, are separated on-site by scavengers; however, waste is disposed of without prior source segregation or component separation, constituting unsorted mixed waste landfilling. The gas, which could be utilized as a renewable energy source, is released into the environment without a gas collection system due to the absence of scientific sanitary landfill design (Aziz & Mustafa, 2018).

Waste composition data used in this study were obtained from the Erbil Directorate of Municipality Services and Environmental Protection (2025) and cross-validated against previously published local characterization studies (Aziz *et al.*, 2011; 2019; 2023). Population data were sourced from official Kurdistan Region Statistics Office (KRSO) statistics (2025). It is acknowledged that no original field gas flux measurements, waste sampling campaigns, or direct LFG monitoring data were collected as part of this study. The reliance on secondary data sources represents a primary limitation, and all results should be interpreted as model-based projections subject to data uncertainty.

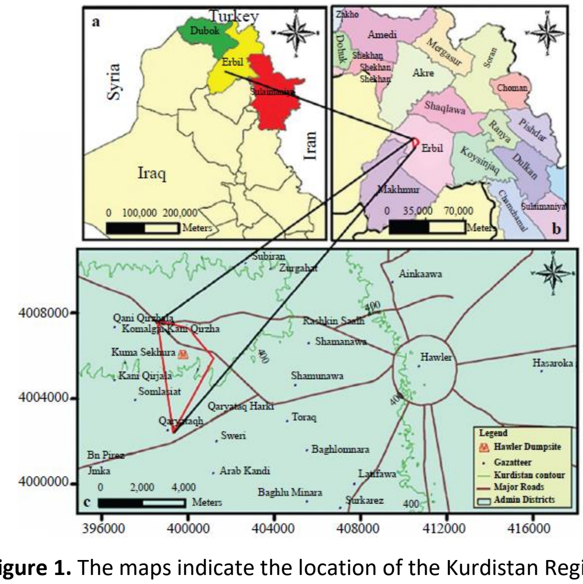


Figure 1. The maps indicate the location of the Kurdistan Region, the Erbil Province in Iraq, and the Erbil landfill site (Gardi, 2017).

2.2. *Population prediction and the development of potential waste in Erbil City*

An estimate of the future population is required to calculate the amount of MSW produced. The urban population of Erbil City and around it was determined to be 1774885 in 2024 by the Kurdistan Region Statistics Office (KRSO). The exponential growth model (Equation 1) was selected to project population and waste generation from 2025 to 2061, as Erbil has experienced consistently rapid, non-decelerating population growth driven by post-conflict urbanization and internal migration (Ismael & Aziz, 2024). This model is more appropriate than linear or logistic approaches over the study horizon, as the city remains far below its estimated carrying capacity.

$$Pn = Po\ (1+ r)\ n \quad (1)$$

Where:

Pn is the number of populations in year n,

Po is the number of populations in the first year,

r is the annual population growth rate ($r = 3.2\%\ yr^{-1}$, based on KRSO census data 2010–2024)

n is the number of years.

The average amount of garbage generated by a population over a certain period is known as the GR, and it is usually expressed in kilograms per capita per day when measuring MSW. It aids planners in forecasting waste amounts for effective management and is impacted by urbanization, consumption trends, income levels, and population size.

To compute GR, use Equation 2.

Total amount of solid waste (tons/ day) = [GR* population]/ 1000 (2)

Affording to research which conducted by (Aziz *et al.*, 2011; Bilal, 2023) the average GR of domestic solid waste in Erbil, Iraq, is 0.654 kg $capita^{-1}$ day^{-1}, used as the model calibration input for the period 2001–2020. For regional context, waste generation rates in comparable Middle Eastern cities range from 0.61 kg/capita/day in Amman, Jordan, to 0.85 kg/capita/day in Baghdad, Iraq, and 1.10 kg/capita/day in Riyadh, Saudi Arabia, reflecting the influence of urbanization and income levels on waste production. Smaller GR were reported in Puducherry, India, and Manila, Philippines. Urban areas have greater GR values of 1.62 and 1.35 kg per $capita^{-1}$ day^{-1}. The average GR of MSW in China is around 0.85 kg per $capita^{-1}$ day^{-1}. The expected solid waste GR range in developing countries is between 0.3 and 1.44 kg $capita^{-1}$ day^{-1}, while developed countries typically generate 1.43 to 2.08 kg $capita^{-1}$ day^{-1}. For the projection period 2021–2031, a future GR range of 0.67–1.34 kg $capita^{-1}$ day^{-1} is applied as low-growth to high-growth scenarios, based on (Aziz *et al.*, 2019; 2023). This range is therefore distinct from the historical calibration value and reflects scenario-based projections rather than a contradiction in reported data.

2.3. *Methane generation model*

LandGEM and IPCC can be utilized in two models according to predefined parameters or site-specific data.

2.3.1. LandGEM model (v3.02)

An automated estimating technique for LFG emissions is the LandGEM model, which was created by the US Environmental Protection Agency (USEPA). Real field data, such as landfill opening and closing years, design capacity, and yearly trash deposits, are used. In this study, annual waste acceptance rates (Mg/year) were derived for each year from 2001 to 2031 by multiplying the projected population by the per capita waste generation rate. These annual Mi values were input into the LandGEM model for each calculation year, enabling year-by-year emission estimation over the full modelling period. The model takes into account variables such as landfill trash's decay rate and methane potential capabilities, in addition to waste biodegradability, microbial consumption rates, volatile solids concentrations, availability of micronutrients, pH, moisture, temperature, and waste composition (Chandrasekaran & Busetty, 2022). The equation used in the LandGEM (v3.02) model is shown in the Equation 3.

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} K \cdot Lo\left(\frac{Mi}{10}\right) \cdot e^{-kt_{ji}} \quad (3)$$

Where:

Q_{CH4}: Annual CH_4 generation in the calculation year (m^3/ year).

i : 1 - year time increment.

M_i : In i^{th} year waste mass accepted (Mg)

n: (year of the calculation) - (initial year of waste acceptance)

t_{ij}: In the i^{th} year age of the j^{th} section of the waste mass M_i accepted

j: 0.1year time increment.

k: CH_4 generation rate ($year^{-1}$).

L_0: potential CH_4 generation capacity (m^3/ Mg).

Table 1. Values for Methane Generation Rate (k) and Potential Methane Generation Capacity (L_0) (EPA, 2006).

Default Type	Landfill Type	*k* Value $year^{-1}$	*Lo* Value m^3/Mg
CAA	Conventional	0.05 (default)	170 (default)
CAA	Arid Area	0.02	170
Inventory	Conventional	0.04	100
Inventory	Arid Area	0.02	100
Inventory	Wet (Bioreactor)	0.7	96

The Methane Generation Rate (k) is a critical element in landfill waste management, defining the methane generation rate. Temperature, pH, availability of nutrients, and moisture content are some of the variables that affect it. Site-specific k values are calculated in 1/year or $year^{-1}$ using EPA Method 2E (EPA, 2006). For traditional landfills, the default k value for arid area landfills is the Clean Air Act (CAA). In addition, for L_0, LandGEM employs default values depending on waste type and composition; higher cellulose content results in higher Lo values. For conventional landfills, the default L_0 value is the CAA L_0 value as shown in **Table 1**.

In this study, the CAA default values (k = 0.05 $year^{-1}$; L_0 = 170 m^3/Mg) were adopted for the Erbil City landfill. No site-specific field calibration was conducted due to the absence of active gas monitoring infrastructure at the site. The selection of k = 0.05 $year^{-1}$ is justified by Erbil's semi-arid Mediterranean climate (~400 mm/year rainfall), which places it above the hyper-arid threshold where k = 0.02 would apply.

2.3.2. *IPCC model*

The IPCC Tier 1 default method was applied in this study. Tier 1 was selected due to the absence of country-specific Tier 2 parameters for Iraq. Unlike the IPCC Tier 2 First Order Decay (FOD) method which is mathematically equivalent to LandGEM and incorporates time-dependent decay the Tier 1 approach calculates CH_4 emissions as a direct function of annual waste input mass without time-dependent decay kinetics. This is why IPCC Tier 1 systematically produces higher and more linearly increasing emission estimates compared to LandGEM, particularly in later years after waste acceptance ceases. As noted by Dalmo *et al.* (2019), CH_4 production decays with time, which the IPCC Tier 1 method does not account for, leading to overestimation. The estimations of CH_4 emissions from the landfill were performed using Microsoft Excel 2007 spreadsheets in accordance with IPCC guidelines (IPCC, 2006a), as delineated in Equation 4:

$$CH_4 = \frac{W * Lo}{\rho CH_4} \quad (4)$$

Where W is the total amount of MSW disposed at the landfill site, L_0 is the potential methane generation from the MSW and ρ_{CH4} is the methane density taken as 0.717 kg/m^3 (Ogunjuyigbe *et al.*, 2017). The value of L_0 can be defined from Equation 5:

$$L0 = MCFx * DOC * DOCf * F * 16/12 \quad (5)$$

Here, MCF (Methane Correction Factor) adjusts for the portion of MSW that effectively produces CH_4 in landfills, as detailed in **Table 2**. DOC (Degradable Organic Carbon) represents the carbon content susceptible to decomposition, while DOC_x denotes the fraction of biodegradable DOC that undergoes degradation. F signifies the proportion of CH_4 within the generated biogas, and the ratio (16/12) is the molecular weight conversion factor from carbon (C, MW = 12 g/mol) to methane (CH_4, MW = 16 g/mol), converting degradable organic carbon mass to equivalent methane mass.

Table 2. The value of MCF recommended in the (IPCC, 2006b) Guidelines.

Type of waste disposal site	MCF default values
Managed – anaerobic	1.0
Managed – semi-aerobic	0.5
Unmanaged – deep (>5 m waste) and high-water table	0.8
Unmanaged – shallow (<5 m waste)	0.4
Uncategorized landfill	0.6

Also, Equation 6 can calculate the fraction of degradable organic carbon DOC (Plant *et al.*, 2022).

$$DOC = 0.4A + 0.17B + 0.15C + 0.3D \quad (6)$$

Where:

A: percentage MSW i.e. paper, cardboard, and textile.

B: percentage of MSW that is yard waste, park waste, or another non-food organic putrescible.

C: percent MSW, which is food waste.

D: percentage of MSW in wood or straw.

The fraction DOC_f dissimilated can be calculated by Equation 7 (Johari *et al.*, 2012).

$$DOCf = 0.014\,T + 0.28 \quad (7)$$

Where:

T: Atmosphere Temperature of the study area.

The following parameter values were adopted for the Erbil City landfill: DOC = 0.18, calculated from Equation 6 using Erbil's waste composition; DOC_f = 0.70, calculated from Equation 7 using the local annual mean temperature (T = 20°C); MCF = 0.8, from **Table 2** for an unmanaged deep landfill (waste depth >5 m); F = 0.5 (IPCC default CH_4 fraction in biogas); and an oxidation factor of 0 (no engineered cover present).

2.4. *Energy Potential and Gross Revenue Estimation*

The next stage entails turning the captured methane into electricity, and Equation 8 can be used to calculate the potential power production. This method can be used to calculate the potential for producing energy from CH_4 gas produced at waste sites in Erbil City. Landfill stations that had previously been converted to ordinary discharge gas were recovered after leachate treatment and utilized to generate sustainable electrical energy (Ep) from Equation 8 (Rodrigue *et al.*, 2018).

$$Ep = \frac{LHV_{methane} * 0.9 * Q\,CH_4 * \lambda * \eta}{3.6} \quad (8)$$

Ep: sustainable electrical energy.

LHVMethane: is the lower calorific value of methane and is given by 37.2 (MJ/m3).

QCH4: annual methane production in the year of the calculation (m3/year).

$\boldsymbol{\lambda}$: is the collection efficiency (75%).

$\boldsymbol{\eta}$: is the electrical conversion efficiency for a given internal combustion engine at 33%.

3.6: is the conversion factor from MJ to kWh.

0.9: is the empirical coefficient.

The calculated electricity generation (in kWh/year) was multiplied by the prevailing market tariffs for industrial and commercial sectors in Erbil to estimate potential revenue as shown in Equation 9. The KRG's 2024–2025 pricing (Runaki project) was used, ranging from 160 to 185 IQD/kWh, equivalent to $0.12 to $0.14 per kWh based on current exchange rates (KRG, 2025).

$$\text{Revenue} = \text{Energy (kWh)} \times \text{Tariff} \quad (9)$$

3. Results and Discussions

3.1. *Forecasting Municipal Solid Waste Generation*

The generation of MSW is influenced by a complex interplay of demographic trends, economic development, and consumption patterns. The GR of household solid waste in Erbil City, Iraq, has been extensively studied, with findings varying across different provinces. In an urban community in Ghana, the GR was 0.68 ± 0.24 kg/capita/day, while in Tulsipur, it was 330.4 g/C/d. In Mexico, the GR was 0.631 and 1.047 kg/C/d, while in Erbil City, it was 0.420 kg/C/d, which increased to 1.27 kg/C/d in 2017. Factors such as recycling, lifestyle, income, rural and urban areas, and SWM pointedly influence the GR and density of produced solid waste (Aziz, 2023).

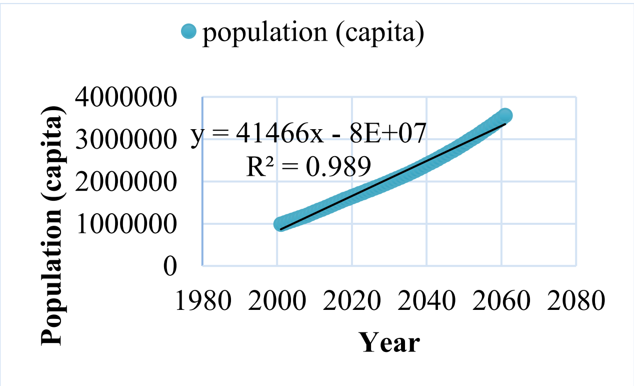


Figure 2. Forecasting model for the population in Erbil City- Iraq.

Additionally, **Figure 2** shows the linear equations used to compute the population prediction for Erbil City from 2026 to 2061 and the Kurdistan Region Statistics Office (KRSO) population data from 2001 to 2025. In addition to helping with the planning and construction of a suitable landfill and treatment facility to manage the increasing amount of waste, these data may be used to predict future trends. The coefficients of the regression line are calculated by using the least squares method (KRSO, 2025).

The equation of the regression line: $y = 41466x - 8*10^7$

The total amount of Erbil MSW generated was estimated based on the calculated GR value (at 0.67 to 1.34 kg capita^{-1} day^{-1}) (Aziz *et al.*, 2023; Aziz *et al.*, 2019). The prediction of Erbil MSW for 2025 to 2061 was based on the population growth rate and subsequently on their per capita waste generation as shown in **Figure 3**.

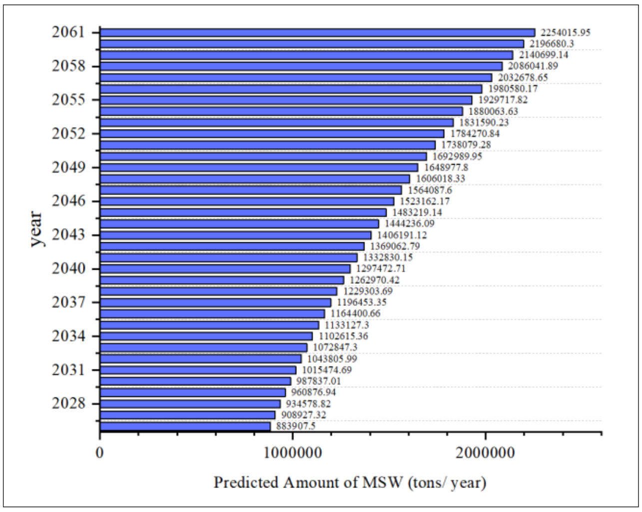


Figure 3. Forecast of MSW Generation in Erbil City from 2026 to 2061.

Food waste is the main supplier to the average GR of 0.654 kg per person per day, according to Aziz *et al.* (2019) studied on residential SWM in Erbil, Iraq. Affording to the study, a sizable portion of materials, such as metals, glass, paper, and plastics, are recyclable. Better trash sorting methods need 88.07% approval, despite how the public views recycling. The garbage is mostly organic and has a potential recycling rate of 85.87% and a fully recyclable rate of 13.79%. Organic waste can be composted to produce nutrient-rich soil additions for local farms and nurseries. For recycling initiatives to be effective, public involvement is essential.

The solid waste was further categorized into distinct sub-components, including food waste (39.5%), yard waste (4.5%), paper and cardboard (6.7%), plastics (25.9%), metals (1.5%), aluminum (0.9), textiles (8.7%), glass (5%), and other wastes (7.4%). **Figure 4** illustrates the average weight distribution of MSW in Erbil City and its landfill site for the year 2025, as reported by the Director of Municipality Services and Environmental Protection in Erbil City-2025.

The high biodegradable fraction particularly food waste at 39.5% of total MSW has direct implications for CH_4 generation kinetics. A higher food waste fraction increases the degradable organic carbon (DOC) input to the IPCC model and elevates the potential methane generation capacity (L_0) in LandGEM, thereby amplifying projected CH_4 production rates.

The projection of MSW generation in Erbil City reflects the combined influence of rapid population growth, urbanization, and consumption patterns. Based on a generation rate of 0.67–1.34 kg/capita/day, total MSW is expected to rise steadily through 2061, with food waste remaining the dominant fraction (≈40%). This composition underscores the high biodegradability of Erbil's waste stream, which directly drives CH_4 emissions potential.

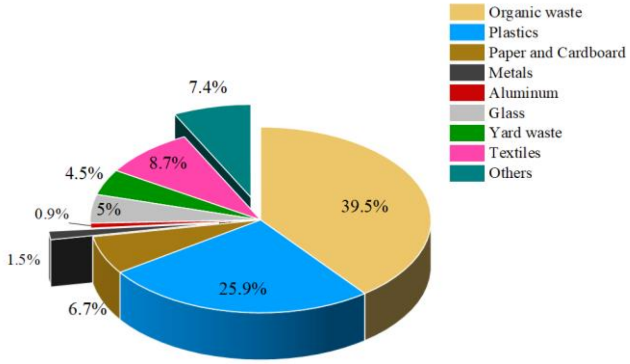


Figure 4. Average weight ratios of MSW components in Erbil City in 2025 the Director of Municipality Services and Environmental Protection in Erbil City- 2025.

3.2. *Predictive Models for the Amount of GHG Emitted in Erbil Landfill*

The LandGEM model makes it easier to quantify the dynamics of waste deposition at the Erbil landfill by differentiating between waste accumulation that occurs after compaction and pre-compaction dumping volumes. This approach to analysis makes it possible to precisely characterize the final amounts of compacted waste at the site as well as the entering waste streams. Results for gas emissions are also provided by the LandGEM model. In addition, **Figure 5** illustrates overall total LFG, CH_4, CO_2, and non-methane organic carbon (NMOC) emissions from the Erbil City landfill site continued until 2140. The Erbil dump site opened in 2001, and the closing prediction year is 2031. Biogas production was nonexistent for the first year of 2001. The LandGEM model expects that the anaerobic breakdown phase starts at least six months after the garbage is dumped in a landfill. Waste breakdown is caused by many reasons, including the waste's composition, moisture content, climate, and covering materials. As well, Mønster *et al.* (2019) highlighted the impact of various factors on CH_4 emissions, including waste nature, pH, rainfall depth, air pressure, humidity, landscape, and microbial interactions. They also highlighted the relationship between LFG components and rainfall, relative humidity, and ambient air temperature, highlighting the need for effective gas collecting systems. Additionally, the variation in CH_4 emissions derived from the LandGEM model may be ascribed to the precision of the input parameters. Default values are frequently used when actual input variables are not available. The emission of CH_4 from open landfills is estimated using LandGEM (v3.02), mostly based on MSWF, k, and L_0 (Chandra & Ganguly, 2023). The baseline k and L_0 values for the LandGEM model were 0.05 year^{-1} and 170 m^3/Mg, and were adjusted to the particulars of the Erbil City landfill site.

In 2032, CH_4 and CO_2 emissions are expected to reach their maximum levels at 5.97×10^4 Mg/ year and 1.638×10^5 Mg/ year, respectively. The landfill's closing in 2031 was the source of the LFG's peak emissions. The projected year when the landfill stops collecting MSW is 2031; as a result, LFG releases will decline. Also, Mønster *et al.* (2019) revealed a peak in CH_4 and CO_2 emissions following the predicted closing year of the landfill.

CH_4 is a gas produced by the anaerobic bacterial decomposition of organic compounds in landfills. Also, CH_4 gas production is directly proportional to the amount of organic garbage in the landfill. Accordingly, a greater amount of organic waste is present when the CH_4 content is higher (Njoku & Edokpayi, 2023). Furthermore, in the LandGEM approach, it is commonly considered that LFG is made up of around 50% CO_2 and 50% CH_4 by volume. Nevertheless, the bulk emissions of CO_2 are greater than those of CH_4 because of variations in molecular weight.

It must be acknowledged that all emission estimates presented in this section are model-based projections. No field gas flux measurements, gas composition data, or direct landfill monitoring data were available from the Erbil landfill site. The results therefore represent theoretical estimates rather than validated measurements. As a literature-based proxy validation, the modeled CH_4 values are consistent with comparable landfills in similar climatic zones: Mokhtari *et al.* (2020) reported peak values of similar order for a semi-arid Iranian landfill, and Chandrasekaran and Busetty (2022) reported 1.87 × 10^7 m^3/year for a smaller Indian landfill, confirming that Erbil's higher value is proportional to its larger waste input.

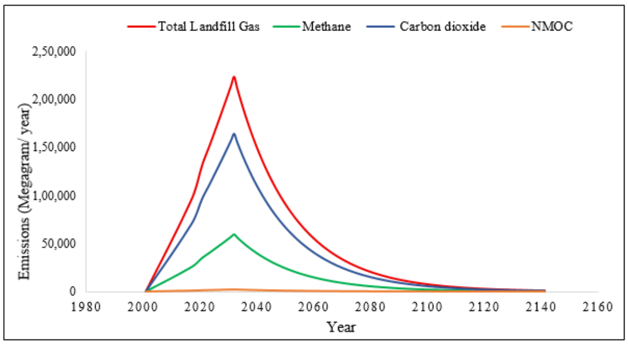


Figure 5. Gas emission from Erbil landfill site using the LandGEM model from 2001-2140.

According to LandGEM's estimations, the Erbil City landfill generated around 46 NMOC compounds in 2032, totaling approximately 715,905.2 m^3/year. NMOC emissions contribute to the photochemical formation of tropospheric ozone a harmful secondary air pollutant through reactions with nitrogen oxides (NO_x) under sunlight. This is entirely distinct from the beneficial stratospheric ozone layer. Rather than improving human health, tropospheric ozone and NMOCs represent significant air quality and public health concerns (Nematollahi *et al.*, 2024). The five highest-emission NMOCs identified in 2032 were Ethane (159,288.9 m^3/year), Toluene co-disposal (30,425.97 m^3/year), Carbon Monoxide (25,056.7 m^3/year), Hydrogen Sulfide (6,443.1 m^3/year), and 2-Propanol (8,948.8 m^3/year). These compounds represent the primary air quality and health concerns associated with the Erbil landfill.

3.3. *Sensitivity Analysis of Methane Emissions*

To assess the robustness of the LandGEM model outputs, a sensitivity investigation was performed for the peak year 2032. The k range of 0.02–0.07 year^{-1} was selected to span the full EPA-recommended range from arid landfill conditions (k = 0.02) to the upper end of conventional landfill values (k = 0.07), with Erbil's semi-arid climate (~400 mm/year rainfall) justifying a mid-range baseline value of k = 0.05. The L_0 range of 100–200 m³/Mg brackets the EPA Inventory default (100 m³/Mg) and a high-organic-content upper bound (200 m³/Mg) appropriate for Erbil's ~40% food waste fraction. The analysis varied the k between 0.02 and 0.07 year^{-1} and the L_0 between 100 and 200 m³/Mg. The baseline scenario, defined by k=0.05 and L_0 =170, produced an estimated CH_4 emission of 8.9 × 10^7 m³/year. Six representative cases were selected to illustrate the range of possible outcomes as shown in **Table 3**.

Table 3. Sensitivity Analysis of CH_4 Emissions Using LandGEM Parameters (Peak Year 2032).

k (year^{-1})	L_0 (m³/Mg)	Estimated CH_4 (m³/year)	Variation from Baseline (%)
0.02	100	4.2 × 10^7	-52.8%
0.03	130	5.8 × 10^7	-34.8%
0.04	150	7.2 × 10^7	-19.1%
0.05	170	8.9 × 10^7	Baseline
0.06	185	1.02 × 10^8	+14.6%
0.07	200	1.15 × 10^8	+29.2%

To identify the individual contribution of each parameter, a one-at-a-time (OAT) analysis was also conducted: k was varied from 0.02 to 0.07 year^{-1} while L_0 was held at the baseline value of 170 m³/Mg, and separately, L_0 was varied from 100 to 200 m³/Mg while k was held at 0.05 year^{-1}. Results indicate that k primarily influences peak emission timing, while L_0 primarily affects peak emission magnitude. The findings show that k and L_0 have a significant impact on CH_4 emissions. Emissions rose by about one-third at the top bound and fell by more than half at the lower bound in comparison to the baseline. Because relying on standard settings may result in a major underestimation or overestimation of LFG potential, this heterogeneity emphasizes the significance of localized calibration of model parameters.

3.4. *Comparison Between LandGEM and IPCC Models*

The study compares CH_4 emissions from the Erbil landfill site from 2001-2032, revealing a peak in emissions in 2032, based on predictions from both models as shown in **Figure 6**. Unlike LandGEM, which applies first-order decay kinetics where emissions depend on the age and quantity of waste already deposited, the IPCC Tier 1 method calculates CH_4 as a direct function of annual waste input mass without time-dependent decay. This fundamental methodological difference explains the divergence between the two models. The values for the IPCC default method ranged from 5.4×10^7 m³/year in the year 2001 which would peak to 1.8×10^8 m³/year in the year 2032, and a gradual linear increase between the two ends, whereas using the LandGEM emission method, no CH_4 emission for the first year which is 2001 then the emission will rise, which would peak to 8.9×10^7 m³/year in the year 2032 then rapidly decline thereafter. This divergence highlights the importance of model selection: LandGEM provides dynamic, time-sensitive estimates, while IPCC offers upper-bound values that may overstate long-term emissions. The factor-of-approximately-two difference between IPCC (1.8 × 10^8 m³/year) and LandGEM (8.9 × 10^7 m³/year) peak estimates has direct infrastructure implications: a gas collection system designed on IPCC values would require approximately twice the pipeline capacity and engine generating capacity compared to a LandGEM-based design. For conservative infrastructure investment, LandGEM is recommended as the design basis, while the IPCC value provides the upper performance bound. The apparent fluctuation in the IPCC curve around 2018–2020 visible in **Figure 6** results from a step-change in officially reported annual waste tonnage from KRSO municipal records for those years, reflecting updated census data. Unlike LandGEM, which produces a smooth exponential decay response due to its first-order kinetics, the IPCC Tier 1 method directly propagates any change in annual waste input into the emission calculation for that year, making it more sensitive to input data discontinuities.

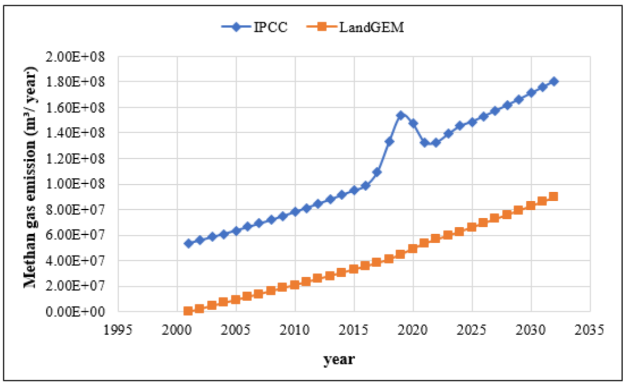


Figure 6. Compares CH_4 emissions from Erbil landfill site during 2001-2032 by using both the LandGEM and IPCC models.

Therefore, the location of waste and garbage disposal significantly impacts the climate and influences both the rise and fall in gas concentrations. As well, Erbil, located in the region has summers that are warm and dry and mild, and rainy winters due to its hot-summer Mediterranean climate (Beck *et al.*, 2023). Long-term garbage presence is a result of this climate's impact on the decomposition of organic waste in landfills. The production of CO_2 and CH_4 by anaerobic decomposition contributes to global warming. Composting and other efficient organic waste management techniques can lower trash volume and CH_4 emissions. To mitigate these consequences for the environment, it is imperative to adopt appropriate waste management practices (Delkash *et al.*, 2016). A comparative summary of the two models is provided in **Table 4.**

Table 4. Comparative Overview of LandGEM and IPCC Tier 1 Models.

Feature	LandGEM v3.02	IPCC Tier 1
Theoretical basis	First-order decay kinetics	Annual mass-balance
Time-dependent decay	Yes	No
Data requirements	Annual waste inputs, k, L_0	Total waste mass, DOC factors
Uncertainty source	k and L_0 parameter values	DOC, MCF, DOC_f values
Emission profile	Rise then decline after closure	Linear increase until closure
Recommended use	Engineering design basis	Upper-bound planning
Peak CH_4 (2032)	8.9×10^7 m^3/year	1.8×10^8 m^3/year

Landfills represent significant point sources of GHG emissions, with direct atmospheric release contributing substantially to climate change and associated public health impacts. However, when designed with proper engineering controls, these sites can transition from environmental liabilities to energy assets (Boongla *et al.*, 2025). The recovered LFGs can be efficiently used as alternative car fuels or as primary energy sources for the production of electricity. He and Qu (2026) demonstrated the potential of modular landfill remediation integrated with AI-assisted grid management as a pathway for waste-to-energy optimization in urban settings. CH_4 flux estimation is a crucial parameter for both environmental impact assessments and energy recovery potential assessments, and the LandGEM model has gained international recognition as a reliable methodology for measuring landfill biogas emissions. It offers estimates of the potential for GHG emissions, including more than 46 gaseous pollutants, both now and in the future. The LandGEM model is appropriate for assessing energy potential because it is available and free. In contrast, the IPCC model understands worldwide trends in CH_4 yield and energy potential and offers generic estimates for countries or the global level. The efficient functioning of landfill gas collection, laws, and waste-to-energy conversion technologies will decide the real manifestation of CH_4 emissions, which are rising as a result of difficulties with landfill operations and waste management (Change, 2006).

3.5. *Energy Production and Gross Revenue Estimation*

LFG to energy technology depends largely on the CH_4 content generated from the landfills, and subsequently, it can be viewed as an energy potential estimation depending on the CH_4 generation potential (Chandrasekaran & Busetty, 2022). Energy recovery calculations assumed a methane collection efficiency of 75% representing the long-term engineering target achievable with a fully installed active gas extraction network and an electrical conversion efficiency of 33%, which is the standard value for landfill gas internal combustion engines (Rodrigue *et al.*, 2018). A plant availability factor of 85% was also applied. It is important to note that since the Erbil landfill currently lacks an active gas extraction system, actual near-term collection efficiency is estimated at 20–40%. A conservative scenario using 40% collection efficiency is therefore also presented in **Table 5** to provide a more realistic near-term estimate. The electrical energy in GWh per year was obtained by LandGEM and IPCC at the Kani Qirzhala Landfill from 2001 until 2032, as shown in **Figure 7**. In 2032, LandGEM predicts 205.98 GWh/year, while IPCC estimates 415.95 GWh/year. Even at the lower bound, this output could supply a significant fraction of Erbil's urban electricity demand, reducing reliance on fossil fuels and enhancing energy security.

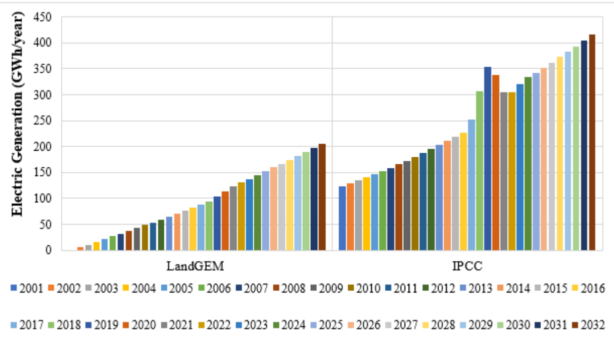


Figure 7. Energy recovery potential from LFG emissions at the Erbil landfill site (2001–2032).

Through real-time monitoring, predictive maintenance, and energy optimization, digital technology including AI-based systems as demonstrated by He and Qu (2026) can optimize power output from LFG engines, identifying inefficiencies and predicting optimal generation scheduling based on energy demand and available LFG (Pheakdey *et al.*, 2023).

For the peak emission year of 2032, the gross revenue estimation reveals substantial energy recovery and revenue potential from the Erbil landfill. The main conclusions drawn from the LandGEM and IPCC models are listed in **Table 5**.

This analysis estimates potential gross electricity revenue only and does not constitute a full economic feasibility assessment. Capital expenditure (CAPEX), operational and maintenance costs (OPEX), gas collection infrastructure costs, discount rates, net present value (NPV), internal rate of return (IRR), and payback period are outside the scope of this study. A dedicated techno-economic feasibility study is strongly recommended before any investment decision is made.

The results of this research clearly demonstrate the energy recovery and gross revenue potential and energy recovery a landfill gas-to-energy (LFGTE) system at the Erbil dump offers. With a projected generation capacity ranging from approximately 206 to 416 GWh/year in 2032, CH_4 -derived electricity could offer a significant, renewable, and reliable supplement to Erbil's power supply. This would immediately help relieve pressure on the national grid, cut reliance on expensive and polluting diesel generators, and so lower the city's overall fossil fuel emissions.

Table 5. Gross Revenue Estimation from CH_4-Based Electricity Generation Using LandGEM and IPCC Models.

Model	Collection Efficiency	CH_4 Volume (m^3/year)	Energy (GWh/year)	Tariff (USD/kWh)	Revenue (USD/year)
LandGEM	75% (target)	8.9×10^7	205.98	$0.12	$24,717,600
				$0.13	$26,777,400
				$0.14	$28,837,200
LandGEM	40% (conservative)	3.56×10^7	82.39	$0.12	$9,886,800
				$0.13	$10,710,700
				$0.14	$11,534,600
IPCC	75% (target)	1.8×10^8	415.95	$0.12	$49,914,000
				$0.13	$54,073,500
				$0.14	$58,233,000

At prevailing tariffs of $0.12–0.14/kWh, gross revenue potential ranges from $10–16 million/year (40% conservative scenario) to $24–58 million/year (75% target scenario). These gross revenue estimates indicate strong economic potential and support the case for investment in gas collection and energy recovery infrastructure. Beyond revenue, such projects would create local jobs, reduce environmental hazards, and contribute to Iraq's renewable energy portfolio (KRG, 2025).

The implementation of LFGTE infrastructure in Erbil faces several practical barriers that must be addressed: (1) Regulatory no specific landfill gas utilization policy framework currently exists in Kurdish or Iraqi environmental legislation; alignment with KRG's renewable energy targets would require new regulatory instruments; (2) Financial the project would likely require public investment or carbon credit revenue under voluntary carbon markets to be viable; access to green finance mechanisms remains limited in the current Iraqi regulatory environment; (3) Technical the existing basic passive gas ventilation pipe system must be upgraded to a fully engineered active gas extraction network before energy generation becomes feasible.

There are significant environmental benefits in addition to the financial ones. By capturing and using CH_4, a GHG with a global warming potential 84 times greater than that of CO_2 over a 20-year period, an LFGTE system would be an effective method of reducing GHG emissions. By converting this potent GHG into a source of useful energy, the initiative would significantly reduce the landfill's environmental impact.

3.6. *Erbil's Solid Waste Management Challenges*

Due in large part to observe a fast urban growth, ineffective collection methods, and poorly run landfills, Erbil is currently dealing with serious challenges in the management of municipal solid waste. Recycling initiatives are still underdeveloped, and the issue is made worse by the increased use of plastics and the low level of public involvement. These flaws limit the city's potential for energy recovery and wider economic gains, worsen environmental deterioration and methane leakage, and raise public health issues.

LandGEM modeling projects peak methane at 8.9×10^7 m^3/year. Gas collection should capture 3.6×10^7 m^3/year initially (40% efficiency), rising to 6.7×10^7 m^3/year (75% target). GIS mapping can guide pipe placement, while AI monitoring enables real-time comparison of measured vs. modeled yields. Sensor-based waste volume tracking will refine annual input data for future calibration.

The Directorate operates under the control of the Erbil Municipalities Presidency, serving six affiliated municipalities along with the Kasnazan Cemetery (under Kasnazan Municipality) and the West Cemetery situated 15 km away on Guyer Road. To sustain urban cleanliness, the city employs 1,300 sanitation workers across six zones, supported by 600 specialized vehicles and machinery, as well as six contracted service providers (Hot Clean, Kahdar, Baghi Prghol, Dazzling Future, Zok, Nrkh, and Class Shtutgart). These companies confirm inclusive waste collection across Erbil's nine urban zones. The municipal authority has established an optimized waste management schedule, achieving 98% coverage through a combination of daily commercial waste pickup and tri-weekly residential collection via door-to-door services. Moreover, the Directorate maintains strict oversight of all sanitation initiatives (JICA, 2022).

A study conducted in New Zanco Village, Erbil City, by Othman *et al.* (2023) aimed to improve MSW management by examining waste production, collection methods, and costs. It found that each person generates 1.114 kg of waste daily, indicating a substantial amount from residential sources. The current waste collection system operates eight times a week, covering a total distance of 321.12 km. By utilizing routing optimization software, the researchers proposed a new collection strategy that reduced the number of cycles to seven, decreased travel distance to 294.03 km, and achieved an operational cost reduction of 8.43%. This represents an estimated annual savings of about $2,730.67, demonstrating effective waste management reduction. Therefore, the research highlights the crucial need to apply scientific tools for both route optimization within Erbil City and overall SWM, which will facilitate better resource recovery, reduced environmental impacts, and enhanced waste management efficiency for this area and similar regions.

In Erbil City, expected recyclable materials include plastics, metals, cartons, and papers, managed through collection by municipal services and private companies. Erbil City's waste management system includes seven collection and transportation companies, complemented by two recycling facilities (Erbil Steel Factory and Med Steel Company) and a waste processing firm (HSE). Notably, Terrapack, a manufacturer of cardboard and paper products, sources its raw materials from Turkey before exporting the processed materials back to a Turkish company for recycling. Similarly, Magic Plastic, a plastic manufacturing enterprise, obtains raw materials from both Turkey and and Iraq, including recycled plastics collected in Basrah. Additionally, HSE specializes in the collection and treatment of industrial waste, including sludge and waste oil generated during petroleum extraction processes (JICA, 2022). The study by Aziz *et al.* (2023) emphasized the possible financial gains of recycling commodities such as paper, metals, plastics, and cartons in Erbil City. The study emphasized the need for increased recycling efforts to decrease waste, produce funding, and improve waste management sustainability. It projects earnings of $175/ton for plastic, $235/ton for metal, and $135/ton for cartons and papers. The **Figure 8** illustrate the current MSWM in Erbil City.

Figure 8. Municipal solid waste management in Erbil City: **a.** Residential area waste collection, **b.** street or commercial area waste collection, **c.** equipment for waste management, **d.** industrial waste collection, **e.** Erbil landfill site, **f.** control room and weighbridge, and **g.** Plastic corrugated pipes for collecting gas emissions.

Erbil City's main dump site for MSWM is the Kani Qirzhala dumping site. The facility is situated on a hill with an elevation of 435 meters above sea level, and its soil ranges from clay loam to silty clay loam. It is currently utilized up to 75% of its area, indicating an urgent need for a new disposal facility before it reaches capacity. However, Erbil City and the Ministry of Municipalities and Tourism - KRG have yet to make progress in this direction. The facility receives waste from Erbil City and three surrounding areas: Salaheddin Nahia, Khabat Qadha Center, and Korakosak Nahia. In 2024, the facility was projected to receive 2300 tons of garbage per day from these local units. With daily cover materials placed, the Ministry of Municipalities and Tourism-KRG has run the facility seven days a week, twenty-four hours a day, since 2004. The disposal site employs 22 people, including a manager, eight equipment operators, six supervisors, three security guards, and a police officer. According to the terms of the supplier's contract, 25 pieces of heavy machinery work in three shifts at the site, and most of them are in acceptable condition. Although the Kani Qirzhala dumping site is an important MSWM facility in Erbil, there are still issues with its maintenance, security, and lack of waste cells and disposal platforms (The Director of Municipality Services and Environmental Protection in Erbil City, 2025).

A study by Aziz and Mustafa (2018) on gas production in the Erbil landfill site revealed that 70 galvanized pipes were initially inserted, resulting in an estimated production of 3,839,669.265 m^3. However, following a visit to Japan in 2023 by the Director of Services and Environmental Protection at the Erbil Municipality, perforated plastic corrugated pipes are now being used. Plastic pipes are preferred over iron pipes as they are approximately 50% cheaper, lighter in weight, easier to fasten, and allow for more efficient gas accumulation due to a larger diameter.

To enhance MSWM in Erbil City, future efforts should adopt an integrated approach designed to prolong landfill operational life. This requires conducting detailed site assessments, implementing waste mining techniques, installing engineered cover systems, and establishing effective leachate and stormwater controls. Subsequent steps involve executing safe closure procedures and maintaining long-term monitoring to safeguard the environment and facilitate low-impact post-closure land use. Prioritizing CH_4 recovery through advanced gas collection and electricity generation infrastructure would contribute meaningfully to local energy security and climate change mitigation.

Effective waste segregation at source, supported by accessible neighborhood collection points and structured incentive programs, must form a foundational element of the system. These measures should be reinforced by adopting modern technologies, including geographic information systems for logistical planning, sensor-equipped bins for fill-level monitoring, and artificial intelligence for route optimization. The operational backbone would further rely on compactor trucks, material recovery facilities, and sanitary landfills equipped with integrated gas recovery and leachate treatment systems. Robust institutional and policy frameworks are equally critical for ensuring accountability and aligning financial flows with environmental objectives. Mechanisms such as Extended Producer Responsibility regulations, public-private partnerships, and targeted economic instruments can provide the necessary governance structure. Concurrently, sustained public awareness campaigns and digital key performance indicator monitoring systems can drive behavioral change and support adaptive management practices.

Ultimately, a commitment to continuous research and local innovation remains essential. Undertaking feasibility studies for technologies like anaerobic digestion, for instance, would generate locally relevant evidence to inform long-term strategic planning. This ongoing learning process will help ensure that Erbil's MSWM system progressively advances toward greater economic sustainability, social inclusivity, and ecological resilience.

4. Conclusions

This study provides the first integrated comparison of LandGEM v3.02 and IPCC Tier 1 models for the Erbil City landfill, Iraq, projecting peak methane emissions of 8.9 × 10^7 m^3/year (LandGEM) and 1.8 × 10^8 m^3/year (IPCC). These correspond to energy potentials of 206–416 GWh/year and gross revenues of $10–58 million/year, depending on collection efficiency (40% conservative, 75% optimistic). LandGEM offers a conservative engineering design basis, while IPCC provides an upper bound for policy and investment planning. All results are model-based estimates derived from secondary data, without field gas measurement or site-specific calibration of k and L_0. Future work should prioritize field monitoring including gas flux probes, periodic CH_4 measurements, and moisture logging to enable model calibration. Economic feasibility remains preliminary; a full techno-economic study incorporating capital costs, payback periods, and financing mechanisms is essential before implementation. Resolution of regulatory, financial, and technical barriers including the absence of a landfill gas policy framework and the need to upgrade the existing passive gas pipe system will also be required. Based on the modeled peak CH_4 of 8.9 × 10^7 m^3/year, prioritizing active gas collection infrastructure capable of 40–75% efficiency is the most directly actionable recommendation from this study.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author thanks the Civil Engineering Department, College of Engineering, Salahaddin University- Erbil, for supporting to conduct of the present research.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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