Journal of Materials and Environmental Sciences
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2019, Volume 10, Issue 10, Page 987-994

http://www.jmaterenvironsci.com

Modeling of municipal solid waste landfill gas generation: a case study, Kirkuk, Iraq

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Received 12 Aug 2019,
Revised 22 Sept 2019,
Accepted 23 Sept 2019

Keywords
- ✓ Kirkuk sanitary landfill,
- ✓ LandGEM model ,
- ✓ Landfill gas emissions,
- ✓ Estimated methane.

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Abstract

Owing to the growing population in Kirkuk, Iraq and the consequent increase in waste production, along with global warming caused by an increase in the concentrations of greenhouse gases, high levels of emissions were observed at the landfill near Kirkuk. In this study, the risk of explosion due to methane formed in landfills and the economic usefulness of utilizing methane were investigated. These emissions can be transmitted by the wind over considerable distances and adversely affect the environment and individual health. In this study, an improved version of LandGem 3.02 was utilized to determine the emission rate of the total landfill gases (i.e., methane, carbon dioxide, and NMOC) emitting from the Kirkuk sanitary landfill in the Kirkuk Governorate in Iraq. The Kirkuk sanitary landfill started working in February 2008. It has a predicted life span of 30 years. The peak output of total LFGs, methane, carbon dioxide, and non-methane organic compounds is 119800, 32010, 87830, and 1376 tons/year, respectively.

1. Introduction

Landfilling is the main method of solid waste disposal. The anaerobic degradation of waste in landfills by microorganisms under favorable conditions results in the emission of landfill gases (LFGs). Methane and carbon dioxide are the major components of landfill gases and are the primary contributors to the greenhouse gas (GHG) effect [1-3]. According to the Kyoto protocol, there are six greenhouse gases that are listed as harmful [i.e., carbon dioxide, nitrous oxide (N_2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and methane (CH_4)] [4-6]. Developing countries generated 29% of GHGs in the year 2000. This quantity is expected to increase to 64% and 76% by 2030 and 2050, respectively [7]. In 2006, the United States contribution to methane release from MSW landfill sites was 23% of the total anthropogenic release. In addition, landfill sites are the second major sources of anthropogenic (GHGs) in the United States. It is expected that 3.8% of the global warming potential (GWP) in the United States is related to methane emissions from landfill sites [8].

The most common and flexible model used to estimate the amount of produced methane in landfills over time is LandGEM (landfill gas emission model). This model was developed by the United States Environmental Protection Agency (USEPA) [9]. The city of Kirkuk is the center of the Kirkuk Governorate. The Kirkuk Governorate is located 238 kilometers to the north of Baghdad (longitude 35.46667º north and latitude 44.31667º east). It is one of the richest oil provinces [10].

The area of the city is approximately 5023 km^2. The city is located 350 m above the sea level; the city experiences a semiarid climate with extremely hot, dry summers and cool rainy winters; the mean annual temperature is 28.7°C, the annual humidity is approximately 48.5%, and an average annual rainfall is approximately 361.3 mm [11].

The landfill near Kirkuk is the first environmentally designed and constructed landfill in Iraq since 2008. The design and construction of Kirkuk's only landfill complies with the US Environmental Protection Agency (US EPA) guidelines for the Class 1 sanitary landfill site and with the European Union Landfill Directive standards. The landfill site is located in Zindanah village of the Kirkuk Governorate, 18 km to the south of Kirkuk between Taza and Laylan [10]

The Kirkuk sanitary landfill accepts waste from domestic and commercial sources, rubber tires, and consumable goods; the landfill has a designed waste capacity of 4.2×10^6 m^3 [12]. Two transfer stations located 17 km and 35 km to the south and to the north of Kirkuk, respectively, were installed to save time and to make waste collection and transportation more efficient. Large metal pieces are the only type of waste that is sought by scavengers for potential recycling. The Kirkuk sanitary landfill was provided with a liner system composed of a 0.6-m thick clay layer with a hydraulic conductivity of 1×10^{-7} cm/s and a 1.5-mm thick high density polyethylene (HDPE) geo-membrane liner [13]. The leachate collection and treatment system is comprised of a 0.52-m gravel drainage layer, a series of 12 perforated PE leachate extraction pipelines with a non-woven geotextile wrap (gravity drained), and chemical dosing and aerobic digestion units [8]. Because there is no gas collection or treatment system attached to the landfill, gases are emitted into the ambient surrounding air. Thus, the aim of this study is to estimate methane gas emissions from the Kirkuk sanitary landfill using the LandGEM model.

1.1. Waste composition of the Kirkuk Governorate

The main waste stream in the Kirkuk governorate is the municipal solid waste (MSW), which includes residential, commercial, institutional, industrial, and public (street cleaning) waste. The Kirkuk MSW composition as inspected at the transfer stations, is shown in Figure 1:

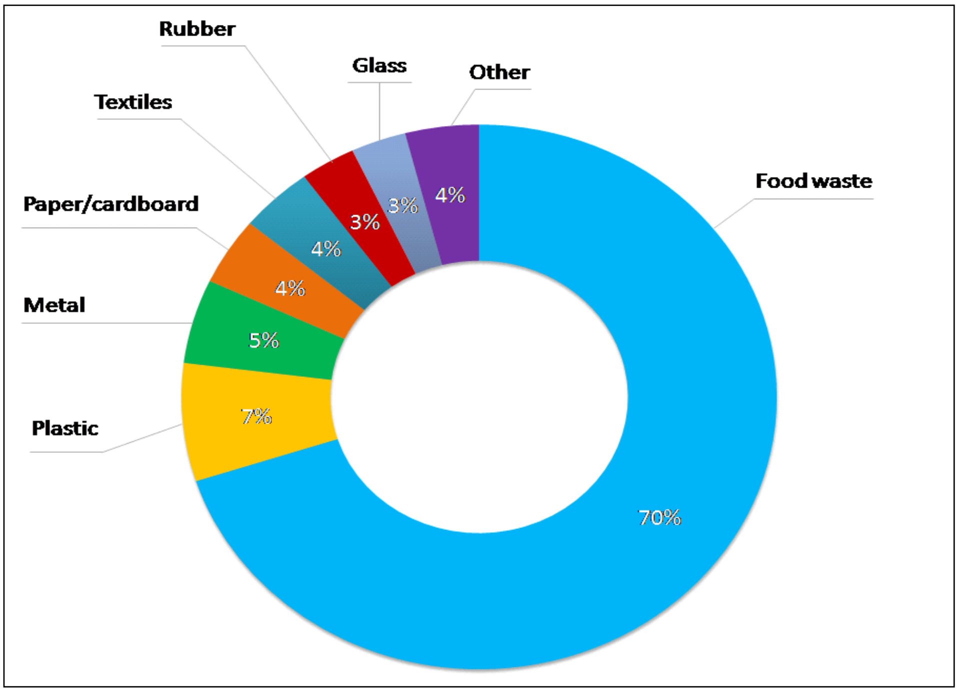

Figure 1. MSW composition as inspected in for Kirkuk transfer station [8] .

1.2. Current status of the Kirkuk landfill

According to the United Nations report, per capita waste production in developing countries is 500–900 g/d·person. According to the Mineral Resources Data System (MRDS, 2008), approximately 800 g of the waste is produced by one person per day in the city of Kirkuk. Solid waste in Kirkuk is expected to increase from 840,000 tons in 2008 to 1,156,445 tons in 2020 owing to high population expansion [13]. The LandGem model suggests a range of 500–900 g/capita/day for citizens in developing countries. According to the environmental

survey performed in Iraq in 2010, 57% of the population in the Kirkuk Governorate is served with waste collection services, which is less than the national average of 66% [10]. Kirkuk can be considered as an average governorate compared with other Iraqi governorate waste collection services, as shown in Fig. 2. The percentages of waste collection service coverage in urban and rural areas were 78.6% and 0.4% compared to the national averages of 91.3% and 7.5%, respectively [14].
The quantities of accepted solid waste at the Kirkuk landfill for the past 10 years were calculated and are shown in Table 3. The quantity of disposed waste generated as municipal solid waste including all types of waste mentioned was approximately estimated to be 310,000 Mg in 2008, which rapidly increased to 550,000 Mg in 2016 because of the war of attrition with Daesh in the neighboring governorates and the considerable number of emigrants that reached Kirkuk [15]. According to Table 3, the total quantity of disposed waste was 4,180,000 short tons by the year 2018, which indicates the rapid increase in municipal and industrial waste generation in this area owing to an increase in the population and commercial products [16].

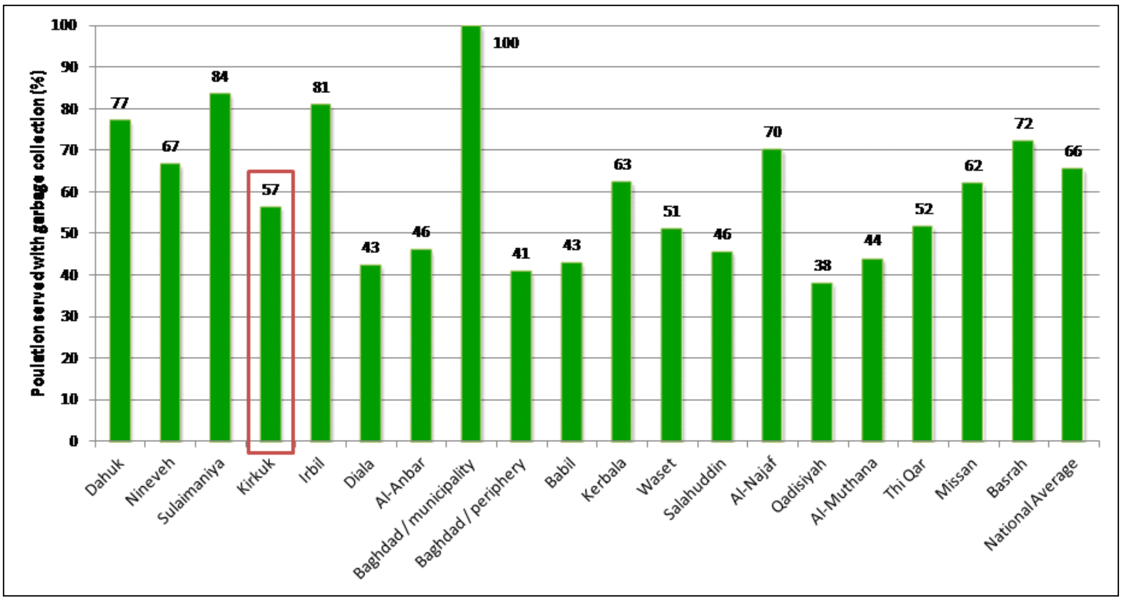

Figure 2. Percentage of population served with waste collection services in Kirkuk and in other Iraqi governorates in 2010[10]

Table 1. Quantities of accepted solid waste at the Kirkuk landfill from 2008 to 2019 [6]

Year	Waste Accepted		Waste-In-Place	
	(Mg/year)	*(short tons/year)*	*(Mg)*	*(short tons)*
2008	310,000	341,000	0	0
2009	315,000	346,500	310,000	341,000
2010	335,000	368,500	625,000	687,500
2011	350,000	385,000	960,000	1,056,000
2012	360,000	396,000	1,310,000	1,441,000
2013	340,000	374,000	1,670,000	1,837,000
2014	350,000	385,000	2,010,000	2,211,000
2015	500,000	550,000	2,360,000	2,596,000
2016	550,000	605,000	2,860,000	3,146,000
2017	390,000	429,000	3,410,000	3,751,000
2018	400,000	440,000	3,800,000	4,180,000
2019	410,000	451,000	4,200,000	4,620,000

* Mg = equivalent one metric ton
*short ton = 0.907 metric ton

2. Materials and methods

2.1 LandGem model

LandGem is the most extensively used model for predicting emission rates for total LFGs including CH_4, CO_2, NMOCs (non-methanic organic carbons) and some particular air pollutants. LandGem is based on a first-order exponential decay rate equation for quantifying emissions from the decomposition of landfilled waste in MSW landfills. The model is in the form of an Excel workbook with several sheets. The software was developed by the Technology Control Center of USEPA. In this study, LandGem (Version 3.02, USEPA, 2005) was used to estimate LFG emission. The LandGem emission methodology can be described mathematically as [1]:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} K\, L_{\circ} \frac{M_i}{10}\; e^{-kt_{i,j}} \qquad (1)$$

Where

CH_4 = annual methane gas generation in the year of calculation (m^3/year)

$i = 1$(time increment in years)

n = (year of calculation) − (initial year of waste acceptance)

$j = 0.1$(time increment in years)

k = methane generation constant ($year^{-1}$)

L_0 = potential methane generation capacity ($m^3\ Mg^{-1}$)

M_i = mass of waste in the i^{th} year (Mg)

$t_{i,j}$ = age of the j^{th} section of waste M_i accepted in the i^{th} year (decimal years).

According to the abovementioned equation, the required inputs for estimating the amount of generated LFG are the design capacity of the landfill site, the annual acceptance rate, the LFG generation constant *k*, the LFG generation potential L_0, and the years of waste acceptance, as shown in Table 1. In this study, the key constants of k and $L0$ were determined from Tables (2) and (3). The NMOC concentration for the clean air act default is 4000 ppmv for the hexane and methane volume content of 50%.

The generation rate (*k*) value depends on the amount of waste moisture, pH, temperature, and nutrient availability for methanogenic bacteria. The default *k* value proposed by USEPA is 0.05/year.

Table 2. Default values for the methane generation rate (k) based on the LandGEM model

Default type	Landfill type	$k$value ($year^{-1}$)
CAA	Conventional	0.05
CAA	Arid Area	0.02
Inventory	Conventional	0.04
Inventory	Arid area	0.02
Inventory	Wet (bioreactor)	0.7

In addition, the World Bank has a guideline for estimating the *k* value. Specifically, the moisture and biodegradation rate of waste components are considered. The recommended *k* values of waste components for different conditions are presented in Table 3.

Table 3. k values ($year^{-1}$) of waste components for different precipitation conditions based on the World Bank recommendation [13]

Recommended *k* values			
Annual rain fall	Slow biodegradation	Moderate biodegradation	Rapid biodegradation
< 250 mm	0.01	0.02	0.03
> 250 mm to < 500 mm	0.01	0.03	0.05
> 500 mm to < 1000 mm	0.02	0.05	0.08
> 1000 mm	0.02	0.06	0.09

On the basis of the components of waste entering the landfill in 2008 and the amount of annual precipitation of 365 mm, the constant *k* values were calculated, as shown in Table 4.

Table 4. k values (year $^{-1}$) calculated on the basis of the components of waste in 2008 and the annual rainfall of 365 mm in Kirkuk

Material	Percent	Slowly biodegradable	Moderately degradable	Rapidly degradable
Food waste	70	-	-	70
Paper and paper cardboard	4	3	1	
Textiles	4			
Wood	3	3	-	-
Plastics, glass, and metals	19	-	-	-
Total	100		1	70
Total × k values		6 × 0.01 = 0.06	1 × 0.03 = 0.03	70 × 0.05 = 3.5
Final k (year^{-1})	0.03			

The value of L_0 strongly depends on the organic fraction of the landfilled waste. This parameter is estimated on the basis of the carbon content of the waste, biodegradable carbon, and a stoichiometric conversion factor. If valid data are available on the quantity and quality of the waste, $L0$ can be calculated using the methods described in different references. The World Bank recommends a method to estimate the value of $L0$ (Table 5).

Table 5. Estimation of L_0 (m^3/ton) on the basis of waste components [2]

Biodegradability	Minimum value of L_0	Maximum value of L_0
Slowly biodegradable waste	5	25
Moderately biodegradable waste	140	200
Rapidly biodegradable waste	225	300

The estimated values of k and L_0 considerably affect the LFG calculation. Because the maximum values of the assumptions will result in invalid results, the minimum value of L_0 (L_0 = 200) was used. In this study, to calculate k and $L0$, the quality of landfilled waste in 2008 was considered as the index for the entered waste into the landfill site for the time period from 2008 to 2038.

Table 6. Description of the supplementary input data to implement the LandGEM model

Input review	
Year the landfill was opened	2008
Year the landfill will be closed	2038
Designed waste capacity	15 million ton
Does the year of landfill closure require a computing model?	No
Methane generation constant	0.03 year^{-1}
Potential methane generation capacity	200 m^3 Mg^{-1}
Concentration of non-methane organic compounds *(NMOC)*	4000 ppmv
Methane content	50% volume rate

The LandGem model assumes a one year time lag between the placement of MSW and landfill gas generation. Landfill gas emissions decrease exponentially as the organic fraction of the landfilled MSW becomes exhausted. As the numerical amount of k increases, the rate of methane production will also increase. The gas production potential, which is suggested by the USEPA model and used in a number of papers, is 170 m^3/ton. However, the waste in this study has a higher percentage of putrescible waste; thus, the gas production potential is 200 m^3/ton, which is similar to the studies by Pascarelli [9] and Ghasemzade [1]. The gas production potential has been estimated in a number of other studies and is reported to be 100 m^3/ton.

In most previous studies, the proposed USEPA parameters were used to estimate the methane production rate and gas production potential, and the results were obtained on the basis of these parameters. It should be noted that these parameters are estimated for the locations and type of waste in the USA.

3. Results

According to the current data model, the mass production and quantity of gas was predicted for the time period from 2008 to 2148 in the Kirkuk landfill using LandGem. As shown in Figures 3 and 4, gas emissions begin a few months to one year after the waste is accepted. After the landfill closure, gas emissions reach peak concentrations and then slowly decrease. The decline continues for 40 to 100 years. The highest gas generation will occur in 2038. The total amounts of LFGs, methane, carbon dioxide, and non-methane organic compound are 119800, 32010, 87830, and 1376 tons per year, respectively.

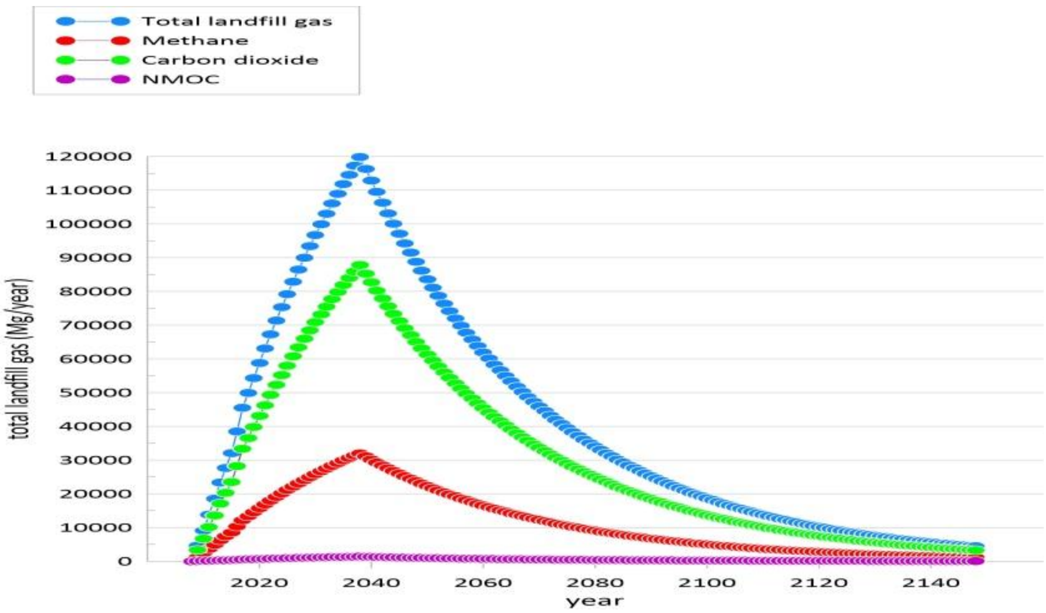

Figure 3. Mass of gases emission of by the Kirkuk landfill site for the time period years of 2008– 2148 (Mg/year).

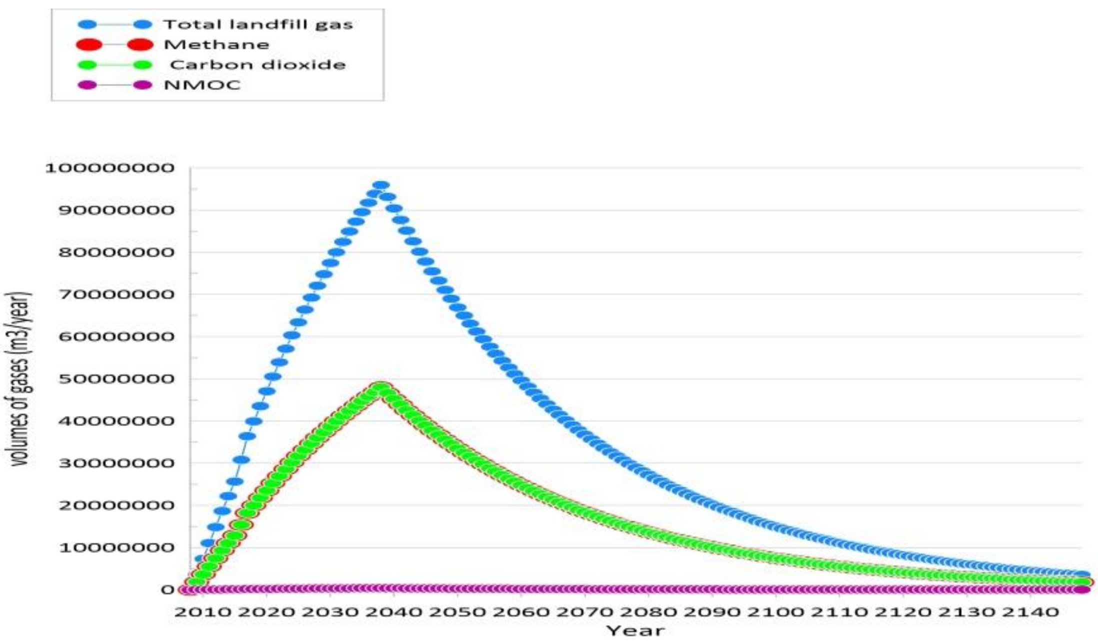

Figure 4. Volume of gases emission of by the Kirkuk landfill site for the time period years of 2008– 2148 (m^3/year).

In addition, in 2038, the volume rates of gas emissions from the landfill will be 5.176×10^7, 2.588×10^7, 2.588×10^7 and 2.070×10^5 m^3/year for total LFGs, methane, carbon dioxide, and non-carbon organic compounds, respectively. Considering that more than 70% of buried waste is putrescible materials, the rate of emitted gas will be very high before the land fill closes in 2038. The steep slope of the curves in Figures 3 and 4 is clearly shown. One year after the closure of the landfill, an increase in the rate of gas generation reaches its peak level. However, with a decreased organic waste content and reduced biological activity, the rate of gas generation will gradually decline in the following years. On the basis of the assumptions used in the model, the emission amount of carbon dioxide and methane is the same, and the emission amount of total LFGs is twice that of methane (Figure 4) [4].

In a study conducted in 2013 in the city of Kirkuk for the same landfill used in our study, the LandGem software was used to estimate the amount of Kirkuk landfill gases. That study estimated the content of methane at 45%. In addition, the production rate constant of 0.02 $year^{-1}$, the gas generation potential constant of 46 m^3/ton, and NMOC (non-organic methanic carbon) of 600 ppmv were taken into consideration. The calculated amounts of total landfill gases and methane were 29590 and 7308 tons/year, and the volumes of total landfill gas and methane were 2.434×10^7 and 1.095×10^7, respectively. By comparing these results with those in our study, it is clear that the obtained values are twice as large as those from 2013 owing to the differences in the assumptions for k and L_0.

In a study, conducted in 2013 in the city of Sanandaj, Iran, the LandGem software was used to estimate the amount of landfill gases. It was determined that the content of methane was 50%, and the methane production rate constant of 0.045 1/year and the gas production potential constant of 200 m^3/ton were taken into consideration. The calculated amounts of landfill gases (e.g., methane, carbon dioxide, and NMOC) over 20 years were 23150, 6184, 16970, and 266 tons/year, respectively [17].

In another study, conducted in 2017 in the city of Jifrot, Iran, the content of methane of 50% was determined, and the methane production rate constant of 0.027 L/year and the gas production potential constant L_0 of 198 m^3/ton were used in the calculation. The maximum concentrations of methane, carbon dioxide and non-methane organic compounds in 30 years will be 40590, 112700, and 1765 tons/m^3, respectively [1].

In another study conducted in 2012 in Malaysia, the LandGem software was used to estimate the amount of landfill gases. The determined content of methane was 50%, and the methane production rate constant of 0.05 L/year and the gas production potential constant of 170 m^3/ton were taken into consideration [18,19]. The obtained results showed that the rate of methane generation from solid waste was 4.436×10^2 (Mg/year) in 2003, which was the first year after the waste acceptance by the landfill, while the maximum methane generation rate occurred in 2012-2015 with the peak generation of approximately 4.17×10^3 (Mg/year).

Conclusions

1- Gas generation will reach a peak value in 2038 at the end of the landfill lifespan. Then, gas generation will slowly decline. This process will continuing for a period of up to 100 years.
2- Gas emissions will slowly decline after the year 2038 and will remain at the minimum level for the time period from 2138 to 2148 as shown in figure (3) and (4).

Acknowledgments

The authors are grateful for information and advices from Engineer Mohammad Ahmed Najem-Aldeen, Environmental Department in Health and Environmental Ministry, Kirkuk, Iraq.

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(2019) ; http://www.jmaterenvironsci.com