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Estimation of gas emission released from a municipal solid waste landfill site through a modeling approach: A case study, Sanandaj, Iran

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Original Article

Abstract
Sanitary landfill is the common strategy for municipal solid waste management in developing countries. Anaerobic decomposition of disposed wastes in landfill under favorable conditions will lead to the landfill gas (LFG) emissions, considering as emerging air pollutants. The emission of greenhouse gases, including methane, resulting from municipal solid waste disposal and treatment processes are considered as the major source of anthropogenic global emissions. Assessment and prediction of the emission rate are important for planning, proper application of methane as an energy source and determining the contribution of various greenhouse gas emissions to global warming. The purpose of this study was to estimate the amount of gas emissions from Sanandaj sanitary landfill. The data about the quantity and quality of the landfill and waste production were collected based on existing standard methods. Using LandGEM software the landfill emissions were estimated with considering the 50% content of methane, the methane production rate constant of 0.045/year and gas production potential constant of 200 m^3/ton. The results of this study showed that the maximum mass of emitted gas is at the next year after the site closure (2021). It was estimated that total mass of LFG, methane, carbon dioxide and non-methane organic compounds were 23,150, 6184, 16,970, and 266 tons/year, respectively. Effective management in controlling LFGs not only results in air pollution reduction, green energy application for sustainable development, but also can use the financial benefits of the clean development mechanism to Kyoto protocol achievement for developing countries.
KEYWORDS: Municipal Solid Waste, Landfill Gases, Methane, LandGEM

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Introduction

Nowadays, one of the major environmental problems facing our world is climate change. In this regard, the developing countries are faced with the highest damage and threats. Mismanagement of solid waste is among the different reasons of climate change. Today, there

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is a worldwide attention to emission of greenhouse gases (GHGs) from municipal solid waste (MSW) treatment and disposal processes as one of the main sources of anthropogenic emissions.[1,2] Developing countries were responsible for 29% of GHGs emissions in 2000. This amount is expected to be 64% and 76% in 2030 and 2050, respectively. Landfill sites are among the main reasons of such increase.[1] In 2006, in the United States, the contribution of methane emissions from MSW landfill sites were 23% of the total anthropogenic emissions. In addition, the landfill sites were known as the second major source of anthropogenic GHGs in the United States.[1] It is also estimated that 3.8% of the global warming potential (GWP) in the United States is related to methane emissions from landfill sites.[3] In Europe, 30% of anthropogenic sources of methane emissions are from landfill sites.[4] Anaerobic decomposition of wastes in landfills by microorganisms under favorable conditions results in landfill gases (LFGs) emission.

Gas production usually begins 2 months after burial of the wastes and continues up to 100 years. LFG typically contains 45-60% methane (CH_4) and 40-60% carbon dioxide (CO_2). It also contain small amounts of nitrogen (N_2), oxygen (O_2), ammonia (NH_3), hydrogen sulfide (H_2S), hydrogen (H_2), sulfide (S_2), carbon monoxide (CO), and non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride.[1,5,6] The amount of methane in the atmosphere has doubled over the last 200 years and this increase, continues, although at a slower pace.[7] In terms of GWP, methane has 25-30 times more effective than CO_2. It is also estimated that the quantitative contribution of CH_4 is about 18% and it has the second rank among GHGs.[4,5,8] Methane has a high heating value, (heating value of a cubic meter of methane is nearly equivalent to that of a liter of kerosene). Thus, it is economically important, too. In addition, when mixed with atmospheric air, methane is explosive in concentrations between 5% and 15% by volume. Therefore, If it is not collected properly and the concentration reaches to the range, it will explode.[2,5] For these reasons, estimation of CH_4 emissions from landfill sites is very important. This estimation also can help to determine the worldwide emissions of different countries. There are several methods for estimating the emissions from landfill sites such as site evaluation, field testing and mathematical modeling.[9,10] In this study, mathematical modeling was applied for LFG emission from the Sanandaj landfill site. LFG modeling is a forecasting model for gas production in the landfill site according to data on waste disposal in past and coming time. Such model will reveal the efficiency of the waste collection system. In addition, the model is an important step in developing a landfill project, which makes it possible to estimate the available recoverable amount of CH_4 as fuel energy over time.[7,11]

Most of these models have been developed based on Monod equation, first-order decay, such as TNO, LFG emissions model (LandGEM), Gassim, Afvalzorg, EBER, IBCC, LFGEEN.[7,11,12] One of the most commonly used and most flexible models is LandGEM. This model that has been developed by the United States Environmental Protection Agency (USEPA), estimates an acceptable amount of produced methane in landfills over time.[13,14] Sanandaj city (the center of Kurdistan province) is located in west of Iran (longitude 47° east and latitude 35° 19' north). The area of the city is about 5023 km^2 and it is 1500 m above the sea level. Its weather is cold and arid. According to the synoptic station in Sanandaj, the city has a mean annual temperature of 14.5° C, annual humidity of about 48.5% and average annual rainfall of about 319 mm. Prevailing wind direction is from south to north of the city. Based on existing statistic data in 2011 the population of the city is about 335,000. The main method for waste disposal is landfilling. The aim of this study is to estimates the methane emissions from Sanandaj sanitary landfill site using LandGEM model.

Materials and Methods

The landfill site of the city has an area of approximately 35 hectares. About 22 hectares of the area have been occupied during operating years. According to the Sanandaj waste management organization (SWMO), this place has been applied as the landfill site since 1993. From 2000 until 2013, about 880,000 tons of waste has been buried in this site. This figure is equivalent to an average of 185 tons of waste per day for a period of 13 years. After 2012, in addition to Sanandaj municipality districts, other wastes from rural areas, industrial and manufacturing centers (within a radius of 20 km from the city) were buried in this site. About 85% of the total produced wastes are disposed at the site, and the rest are recycled or composted. At the site, the wastes are covered by a layer of soil using ramp method as a relatively sanitary landfill. The average depth of waste in the site is approximately 10 meters. In this study, LFG production is estimated based on the assumption of a sanitary landfill that has been launched in 2000 and will be closed in 2020.

Information on the quantity of generated and disposal waste in the landfill is available from 2000 to 2013. The amount of produced waste generation was predicted based on the population growth rate, the rate of waste generation per capita and its changes up to the plan horizon year (2020). To determine the composition of MSW, the necessary data were taken from SWMO. Physical analysis of the waste transported to the landfill site, in the year of 2012, was carried out according to standard methods.[15] Prediction of the changes in the quality and quantity was based on the changes from 2000 to present data, and was compared with changes in the waste components in reliable sources.[2,15]

LandGEM is the most extensively used model for estimating emission rates for total LFGs including CH_4, CO_2, NMOCs 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.[13] The software was developed by Technology Control Center of USEPA. In this study, LandGEM (Version 3.02-USEPA, 2005) was used for estimating LFG emission.[13]

The LandGEM emission methodology can be described mathematically using the following equation:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} KL_0 \left(\frac{M_i}{10}\right) e^{-kt_{ij}}$$

where:

Q_{CH4} = annual methane generation in the year of the calculation (m^3/year)

i = 1 year time increment

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

j = 0.1 year time increment

k = methane generation rate (/year)

L_0 = potential methane generation capacity (m^3/ton)

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

t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year (decimal years, e.g., 3.2 years).

According to the 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.[13] In this study, the key constants of k and L_0 were calculated. The NMOC concentration for the clean air act default is 4000 ppmv as hexane and methane volume content is 50%.[13,14]

Generation rate (k) value depends on the amount of waste moisture, pH and temperature, and nutrient availability for methanogenic bacteria. Based on USEPA guidelines k values of 0.7 and 0.02 are recommended for humid and dry climates, respectively. The default k value proposed by USEPA is 0.05/year.[13] The World Bank also presents a guideline for estimating the k value. In this method, moisture and the biodegradation rate of waste components is considered.[14] Recommended *k* values of waste components for different conditions are presented in table 1.

With respect to the elements of waste entering the landfill in 2012, and the amount of annual 319 mm of precipitation the constant *k* values were calculated as shown in table 2.

The value of L_0 strongly depends on the organic fraction of the landfilled waste. This parameter is estimated based on the carbon content of the waste, biodegradable carbon, and a stoichiometric conversion factor. If valid data is available on the quantity and quality of the waste, L_0 can be calculated using several methods used in different references. The World Bank recommends a method to estimate the value of L_0 (Table 3).[14]

With regard to table 3 and qualitative characteristics of Sanandaj solid waste in 2012, the minimum and maximum values of L_0 are 200 and 269, respectively. The estimated values of *k* and L_0 have substantial effect on LFG calculation. Since the maximum values of the assumptions will cause invalid results, so the minimum value of L_0 (L_0 = 200) was taken into consideration.[7,14] In this study, for calculating *k* and L_0, the quality of landfilled waste in 2012 was considered as the index for entered waste to the landfill site from 2000 to 2020.

Results and Discussion

Current and future status of generated waste in Sanandaj

The population of Sanandaj in 2006 and 2011 was approximately 315,000 and 335,000, respectively. The generated wastes related to these populations were 265 and 310 tons/day, respectively. Accordingly, the per capita waste production was 840 g/day in 2006 and 925 g/day in 2011. United Nations development

Table 1. Different *k* values (/year) of waste components for different precipitation conditions based on the World Bank recommendation[14]

Annual rainfall	Recommended values for k (/year)		
	Slowly biodegradable	Moderately biodegradable	Rapidly biodegradable
< 250 mm	0.01	0.02	0.03
> 250 to < 500 mm	0.01	0.03	0.05
> 500 to < 1000 mm	0.02	0.05	0.08
> 1000 mm	0.02	0.06	0.09

Table 2. Calculated k values (/year) based on the components of waste in 2012, and annual rainfall of 319 mm in Sanandaj

Materials	Percent	Slowly biodegradable	Moderately biodegradable	Rapidly biodegradable
Putrescible	70.5	-	-	70.5
Paper and paperboard	6.5	4.87	1.63	-
Textiles	2.6	2.60	-	-
Wood	1.1	1.10	-	-
Plastic, glass, metals, etc.	19.3	-	-	-
Total	100	8.57	1.63	70.5
Residual components of each group multiplied by the coefficient (k)	-	0.09	0.05	3.5
Final k value (/year)	-	0.045		

Table 3. Estimation of L0 (m3/ton) based on the waste biodegradability14

Biodegradability	Minimum value of L0	Maximum value of L0
Slowly biodegradable	5	25
Moderately biodegradable	140	200
Rapidly biodegradable	225	300

program suggests a range of 500-900 g/capita/day for citizens of developing countries. The average per capita production of solid wastes in Iran in 2000 was estimated about 850 g/day.[15,16] After 2012 in addition to Sanandaj municipality districts, about 20-50 tons/day waste have been transported to the site from different rural areas, industrial and manufacturing centers (within a radius of 20 km from the city). In general, in 2013, about 300 tons/day waste was transported to the site. With regard to increasing in public welfare, and due to the increase in per capita waste generation in recent years, the average rate of the increase in per capita waste generation is estimated to be 10 g/year. Based on the population growth rate, it is estimated that the population exceeds 350,000 in 2020. Accordingly, it is estimated that solid waste generation exceeds 350 tons/day in 2020. Thus, the average per capita will be 1000 g/day. At the end of the project year (2020), total generation of waste (including 50 tons of waste generated in the surroundings) will be 400 tons/day. After determining the amount of produced waste, the amounts of solid waste disposal site (SWDS) and effective portion of solid waste for gas production must be determined. For this purpose, both the quantity of waste and the condition of landfilling is very important. Since some of the generated waste is recycled or composted, conversion factor of MSW into SWDS is considered to be 0.85.[16]

The input waste to the landfill is not properly disposed and in some points, aerobic conditions can be provided due to inadequate coverage. Therefore, the impact factor of 0.7 is considered for waste products contributing to gas production. Table 4 presents the quantity of waste generated in Sanandaj and the effective values in gas production in recent and upcoming years. To determine the waste composition, data from the previous years were received from the SWMO. The physical analysis of waste entering the landfill in 2012 was carried out according to standard methods. Physical composition of the landfilled waste in 2012 is presented in figure 1. Due to the increase in MSW generation per capita per year and assign an increase of 10 g per capita per year to dry waste stream, it is expected by 2020, about 7.5% of the putrescible organic portion is reduced, and the amount of paper, plastics, etc. will increase.[2,15]

Estimation of LFG production

According to existing data model mass production and gas volume in Sanandaj landfill was estimated using LandGEM from 2000 to 2100 (Figures 2 and 3). As can be seen, emissions start a few months to one year after the waste landfilling. It reaches to peak point after the landfill closure and then declines. Based on the condition this decline continues from forty to hundred years.[1,5,6] As shown in figure 2, the

Table 4. The quantity of generated waste and their effective amounts of gas production in recent and upcoming years

Year	Generated waste (tons/day)	Generated waste (tons/year)	Effective amounts of gas production (tons/year)
2000	210	76,650	53,655
2001	210	76,650	53,655
2002	220	80,300	56,210
2003	230	83,950	58,765
2004	240	87,600	61,320
2005	250	91,250	63,875
2006	265	96,725	67,708
2007	280	102,200	71,540
2008	280	102,200	71,540
2009	290	105,850	73,906
2010	300	109,500	76,650
2011	310	113,150	79,205
2012*	350	127,750	89,425
2013	350	127,750	89,425
2014	360	131,400	91,980
2015	370	135,050	94,535
2016	385	140,525	98,368
2017	390	142,350	99,645
2018	390	142,350	99,645
2019	395	144,175	100,923
2020	400	146,000	102,200
-	-	-	-

* After 2012 in addition to Sanandaj city waste, other wastes from rural areas, industrial and manufacturing centers (within a radius of 20 km from the city) have been buried in this site

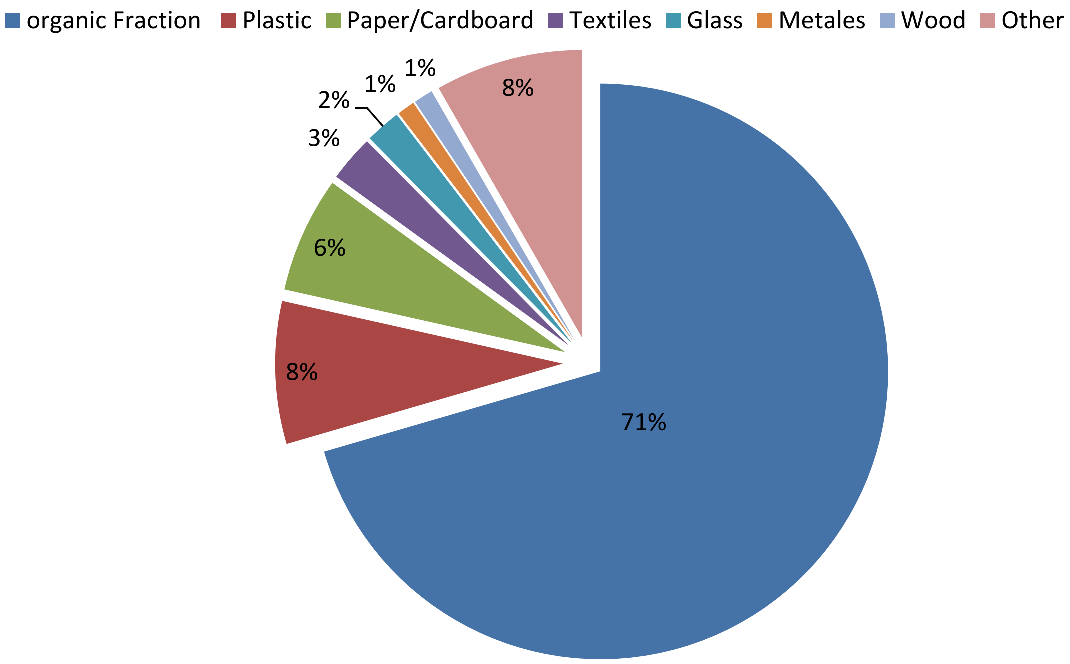

Figure 1. Municipal solid waste component of waste disposed in Sanandaj landfill site in 2012

maximum mass of emitted gas is occurred in 2021. The amount for total LFGs, methane, carbon dioxide and non-methane organic compounds are 23,150, 6184, 16,970, and 266 tons/year, respectively. Also from figure 3, the maximum volume of emitted gas in 2021, volume rates of gas emissions from landfill are 185 × 10^5, 93 × 10^5, 93 × 10^5, 74 × 10^3 m^3/year for total LFGs, methane, carbon dioxide and non-carbon organic compounds, respectively. Considering that more than 70% of the buried waste is biodegradable organic materials, so the period before the land fill closure year (2020), gas production rate will be very high. Sharp slope of the curves in figures 2 and 3 indicates it clearly. After a year from landfill closure the increase in the gas production rate reaches to maximum level, but with decrease in organic matter content of waste and reduction of biological activity, it declines gradually in the next years.[5] According to the assumptions of the model, the emission volume of carbon dioxide and methane are the same, and the emission volume of total LFGs is twice that of methane (Figure 3).[3] According to the report of Iran environmental protection agency, based on the international panel on climate change (IPCC) methodology, methane emissions from MSW landfills in 2000, was estimated about 497.54 Gg.[16]

The results of a study on three municipal landfill in west of Iran, showed that the averages methane and GHGs emissions in the year of 2010 were about 2244 and 8405 ton/year, respectively.[17] Since the rate and volume of produced gas depend on the age and composition of waste, the moisture, geologic conditions, the amount of leachate, landfill waste mass temperature, presence of oxygen and quality of site coverage, thus, comparing the results obtained from this study with other similar studies does not seem very reasonable.[4,5,18,19] As a whole, compared with some other studies, the amount of 6184 tons/year of methane production in Sanandaj landfill is relatively high. High percentage of biodegradable fraction of wastes, as well as the high values of the k and L_0 constants due to the landfill conditions, can be the reasons for such

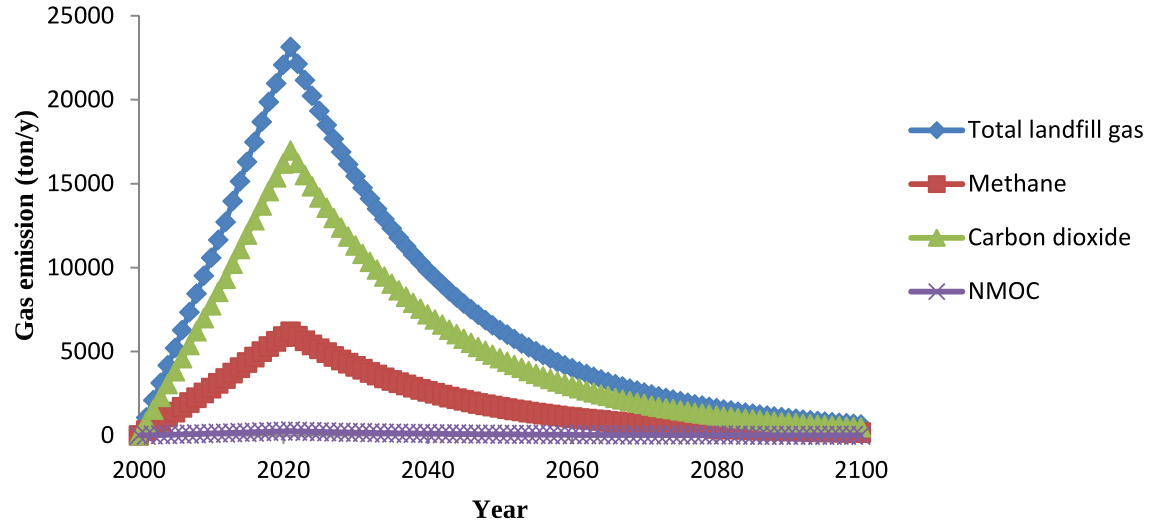

Figure 2. Annual landfill gas mass production provided by LandGEM models (2000-2100) in Sanandaj landfill
k = 0.045 (/year), L_0 = 200 (m^3/ton), non-methane organic compound (NMOC) = 4000 ppmv, methane = 50%

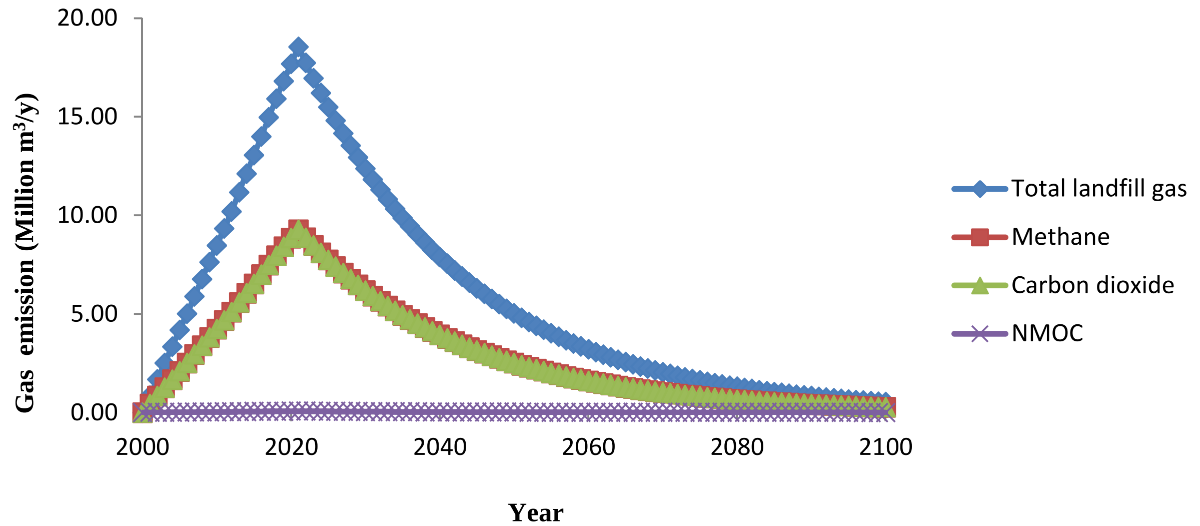

Figure 3. Annual landfill gas volume production provided by LandGEM models (2000-2100) in Sanandaj landfill
k = 0.045 (/year), L0 = 200 (m3/ton), non-methane organic compound (NMOC) = 4000 ppmv, methane = 50%

relatively high gas production. Biodegradability of organic contents is over 70%, while in other studies this value was lower and ranged from 40% to 65%.[3,5] The effect of effective parameters on gas production is considered in terms of *k* and L_0.[7,14] Methane generation rate (*k*) is the rate of waste decay, and the common range is from 0.02/year for dry sites to 0.7/year for wet sites. Values of *k* depend on the moisture, pH and temperature of the waste mass and nutrient availability for methanogenic bacteria. In high levels of *k*, methane production rate increases and after landfill closure gas production declines rapidly.[13,14] In this study, a constant value of 0.45/year was obtained. Similar works reported lower or higher values.[3,5,20] L_0 was actually the potential of methane generated from decomposing a ton of waste calculated based on the carbon content of the waste, waste biodegradability and effect of the stoichiometric conversion factor. Theoretical and operational levels range from 125 to 310 m^3 of methane per ton of waste. The value of this parameter is recommended by the USEPA about 170 m^3/ton of waste. Except dry climates, where methane production is limited, the value of this parameter mainly depends on the composition of the buried waste. Wastes with higher organic matter content have higher L_0 value.[13,14] The values obtained from this study (200 m^3/ton) compared to other studies (average100 m^3/ton) is relatively high.[3,5] NMOCs emission in this study is about 1% of total emissions, which is consistent with its usual emission amount from landfills. In spite of such small amounts, it may be important, because some of these compounds are known as carcinogen and have adverse environmental and health effects.[6] Overall, LandGEM model due to its reliability and close results to actual studies, have been known as the representative of estimating models for LFG emissions.[3,13] However, since this model is unable to consider the differences among various organic contents in MSW, total MSW is taken into consideration. So that, the estimation is slightly higher than that of other models.[11] Obviously, knowledge of the real gas production trend requires accurate knowledge of degradation of waste in landfill condition. Therefore, the work should be conducted in field studies on pilot cells and continuous recording of volume gas production. Along with the environmental conditions, such as ambient temperature, pressure, rainfall, temperature within the waste mass, the pressure of buried waste in cells should be measured and recorded. After a few years, from the trend of changes in gas production the degradation of waste and *k* coefficient can be realized.[1,2,14,15] With regard to high volumes of predicted methane in the landfill site, with good engineering practice in addition to methane recovery, odors, air and of groundwater pollution can also be prevented considerably. By establishing a biogas plant, not only the environmental contaminants are collected, and the public's health is benefited, but also some part of required electrical and thermal energy can be supplied. Thus, production of 5.22 kwh for each cubic meter of waste can be expected.[1,5,10] By controlling and reducing of methane emissions in Iran, we can move up to the sustainable development. In addition, the aim of the clean development mechanism of the Kyoto protocol will be complied, and a part of solid waste management costs will be provided using economic benefit derived from the mechanism.[14,21] Since methane emissions from the waste sector contributed to 10 to 19% of total anthropogenic global emissions; therefore, development of new and environmentally friendly methods is necessary for MSW management.[1,8,22,23]

Conclusion

MSW landfill is one of the major sources of anthropogenic greenhouse gases. If it can be properly managed and emitted gases can be collected and recycled, adverse environmental impacts would be minimized. In this study, the amount of emissions from Sanandaj landfill during 2000 to 2100 was calculated using LandGEM software program. Accordingly, most of the emitted gas mass from the landfill was estimated in 2021. Estimated values for total LFG, methane and carbon dioxide, were 23,150, 6184, and 16,970 tons/year, respectively. Also in this year the rate for total LFG, methane and carbon dioxide were 185× 10^5, 93 × 10^5, 93 × 10^5 m^3/year, respectively. It is obvious that gas generation in landfill depends on many factors that model does not consider them. Thus, the results of this study are merely estimation. In addition to modeling, more accurate results require some knowledge of the real situation prevailing landfill waste decomposition process through pilot field studies and continuous recording of gas producing.

Conflict of Interests

Authors have no conflict of interests.

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