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Calculation of CH_4 and CO_2 Emission Rate in Kahrizak Landfill Site with Land GEM Mathematical Model

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Abstract: Emitted gasses from the landfills are one of the significant sources of air pollution in Iran. Meanwhile, the reduction, control and recycling of such gasses is of great importance from hygienic and global perspectives. Kahrizak landfill site has been a dumping place for the past 40 years. The average amount of wastes disposed at the site is approximately 7000 Tons per day. The purpose of this study is calculation CH_4 (Methane) and CO_2 (Dioxide carbon) emissions and estimate the carbon reduction potential using the Land GEM 3.02 model. Validation of this model was tested by comparing the model estimates with the methane and CO_2 recovery rate compiled from the experimental results of Kahrizak landfill between 1994 and 2004. Based on the model results, the CH_4 and CO_2 emissions between 1992 and 2012 were determined and sensitivity analysis was performed for various quantities of the decay rate. Through gas-recovery and extracting energy from landfills with 75 percent efficiency, the generation rate of greenhouse gases will reduce to around 557,633 tons of CO_2 equivalent in Iran.

Keywords: Emission; Landfill; Gas recovery; Land GEM; Dioxide carbon.

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1. Introduction

Climate change is a serious environmental issue facing the world today, and developing countries are reported to be the ones that stand to suffer the most damages [1-3]. The world is becoming warmer as it experiences the extremes of global climate change. Landfill sites containing wastes undergoing biological decay, specifically in an advanced methanogen stage of decomposition, typically emit high volumes of landfill gas. Landfill gas is widely known to comprise carbon dioxide and methane in part percentages ranging from 40 to 60%. According to the Kyoto Protocol, there are six gases that have been listed as being particularly harmful greenhouse gases (GHG): carbon dioxide (CO_2) , nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFC's) and sulphur hexafluoride (SF_6), methane (CH_4) [4,5]. Atmospheric methane concentrations have increased by 30% in the last 25 years and multiplied by a factor of 2–3 since the 1700s due to human activities. This methane addition has increased radioactive forcing by 0.47 (W/m^2)(IPCC,2006). Approximately 70% of methane emissions are anthropogenic (e.g., agriculture, natural gas activities, landfills, etc.) and 19% (70 Tg/year) of these are attributed to landfill gas generation [4-5]. Emitted biogas quantification from dumps is one of the objectives foreseen in the Kyoto protocol; indeed it is important to both evaluate what the contribution of landfills is on the total production and to identify measures that should be adopted for the reduction of these emitted gases. The refuse treatment plants and the recovery during the combustible extraction phases could have economic benefits that may partly cover additional costs of the necessary interventions to reduce biogas levels, such as preventing the escape of biogas in the proximity of the dumps. Nevertheless, the evaluation of biogas emissions from the dumps is not simple, since these are multiple point sources with a high spatial and temporal variability [6]. A sanitary landfill is usually conceptualized as a biochemical reactor. In this giant reactor, waste and water are the main inputs, while gas and leach ate are the major outputs. Landfill gas is the result of biological anaerobic decomposition of organic materials in landfills. The principal constituents present in landfill gas are methane (CH_4) and carbon dioxide (CO_2), but landfill gas is commonly saturated by water vapor and presents small quantities of non- methane organic components and various other trace compounds. Since methane is produced only during the anaerobic decay of organic matter, and not during aerobic decay, the diversion of organic waste from landfills to composting reduces methane production [7]. Also, landfill gas can be collected to heat nearby industrial or agricultural operations or to produce electricity, which can be sold to the power grid. Landfill gas utilization provides a source of revenue, replaces fossil fuel use, and reduces greenhouse gas emissions [7]. The main focus of this study was to calculate the CH_4 and CO_2 emissions and estimating the potential for carbon reduction using the LandGEM 3.02 model. In order to achieve this goal, two main areas in Kahrizak landfill that are presently collecting and beneficially using landfill gas (LFG) have been studied and gas emission data from the case study landfills ha been modeled. In addition to environmental benefits, the LFG reduction projects can yield economic benefits, if properly managed because of viable market usages of methane primarily for direct usages such as industrial heat plants or for electricity production. Methane from LFG can be a source of renewable energy production, since LFG has a heating value of 20.5 (MJ/ m^3). A waste management strategy is currently being prepared by the Municipality of Tehran, which will include a landfill management strategy for the closure of the Kahrizak Landfill facility, and installation of a gas recovery system. As a consistent and accurate forecast of the potential landfill gas yields is difficult due to the large variations in land filling methods used over the past 30-40 years at the very large site at Kahrizak, analyzing the landfill gas potential using, with LandGEM model has been done for sustainable gas yields over a time scale of every year. The main objective of this study for Kahrizak landfill is as follows:

- Analyze of field data on landfill gas flows
- Estimation more accurately the landfill gas volumes based on field data
- Prepare a preliminary design that takes into consideration the correct order of magnitude of gas volumes in terms of capacity

2. Methane generation model

Landfill gas models describe in simple terms the complex changes occurring during landfill decomposition to estimate methane generation over time. Table 1 shows formulas for four models including one zero-order model and three first-order models. The zero-order model, EPER model, generates the rate of methane production independent of the amount of substrate remaining or of the amount of biogases already produced. The German EPER model roughly approximates methane generation from operational landfills, but not from the non-operating landfills. Although complete anaerobic decay of organic waste in landfills requires many years, EPER only considers the last year's waste input to estimate methane generation [8,9]. Methane generation at landfills is generally modeled using a first-order kinetic equation [10-13] based on waste amounts over time, waste composition, and other factors. In first-order models, methane production is assumed to be in a steady, linear decrease over time proportional to the degradation of organic matter in any given year and the remaining fraction of organic matter from previous years [11]. Each year's waste follows a decreasing exponential trend in gas production until it is completely degraded [15]. Thus, according to these model assumptions, a gradual decline in landfill gas would occur post-closure. First-order models, including TNO, Belgium, and Land GEM, are currently used by Denmark, the Netherlands, and the United States, respectively [12-13].

Table 1. The formulas for four existing landfill gas generation models [14]

LFG model	Model formula	Symbol index
German EPER model	$Q = (M)\ (\mathrm{DOC})\ (\mathrm{DOC}_f)\ (F)\ (D)$	Q : Methane production (kt/yr)
		M : Waste generation (Mt/yr)
		DOC : Degradable organic carbon (kg/tonne)
		$\mathrm{DOC_f}$: Fraction assimilated DOC
		F : Fraction of methane in landfill gas
		D : Collection efficiency factor
TNO model	$Q = (\mathrm{DOC}_f)(1.87)(M)(\mathrm{DOC})(k)e^{-(kt)}$	Q : Methane production (kTone/yr)
		DOC: Fraction of assimilated DOC
		M : Waste generation (Mt/yr)
		DOC : Degradable organic carbon (kg/Tone)
		k: Decay rate (yr^{-1})
		t: Time of waste disposal (yr)
Scholl Canyon	$Q = (M)(k)(Lo)\ \exp-(kt)$	*Q:*= methane production (kt/yr)
		M : waste generation (Mt/yr)
		k : decay rate (yr^{-1})
		Lo : methane generation potential (kg/tonne)
		t : time of waste disposal (yr)
LandGEM version 3.02	$Q_{CH4}=\sum^{n}{}_{i=1} \sum^{1}{}_{j=0.1} kL_0\ (M_1/10)e^{-kt}{}_{ij}$	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
		j: 0.1 year time increment
		k: methane generation rate(year^{-1})
		L_0: potential methane generation capacity(m^3/ton)
		M_i: mass of waste accepted in the ith year (ton)
		t_{ij}: age of the jth section of waste mass M_i accepted in the ith year

2.1. Land GEM model

Land GEM is based on a first-order decomposition rate equation for quantifying emissions from the decomposition of land filled waste in municipal solid waste (MSW) landfills. The software provides a relatively simple approach to estimating landfill gas emissions. Model defaults are based on empirical data from U.S. landfills. Field test data can also be used in place of model defaults when available. LandGEM3.02 model calculates methane yield based on four key inputs. The first necessary input is waste amounts deposited in landfill over all the years that the landfill has been operational. The second input is the Degradable Organic Content (DOC), which represents the waste portion available for microbial degradation into landfill gas [16]. The organic fraction of each type of organic waste is considered as all having different decay rates.

$$\mathrm{DOC} = (0.4 \times \mathrm{A}) + (0.17 \times \mathrm{B}) + (0.15 \times \mathrm{C}) + (0.30 \times \mathrm{D})[\text{all units wet weight(w/w)of kg carbon/kg waste}] \quad (1)$$

where *DOC* is degradable organic carbon, *A* is fraction of municipal solid waste (MSW) that is paper and textiles waste, *B* is a fraction of MSW is the garden or park waste, *C is a* fraction of MSW is food waste, and *D* is a fraction of MSW is the wood or straw waste. Another input is the decay rate (k) is the biodegradation half-life in years^{-1} for organic material in a landfill. The IPCC (2006) recognizes the high uncertainty and error associated with k. The decay rates range from one to 50 years and even longer in landfills located in dry, cold climates. Decay rates have been determined by a number of methods: laboratory simulations [17], samples excavated from landfills [18-19], and test cells designed to simulate real world conditions [20]:

$$\mathrm{k} = 3.2 \times 10 - 5(\mathrm{x}) + 0.01 \quad (2)$$

where k is a decay rate (year^{-1}), and x is an annual average precipitation for the interested period for the area where the landfill is located. The methane generation potential (Lo) is the percentage of methane in the landfill gas multiplied by DOC and the other factor represents the amount of methane produced per tonne of waste land filled. The Lo multiplies DOC and DOC$_f$, to the fraction of methane in the landfill gas and other factors. The higher the cellulose content of the refuse, the higher is the value of L_0. The value of L_0 ranges from 6.2 to 270 m^3/ Mg refuse. The EPA default value of L_0 is 170 m^3/Mg refuse.

$$\mathrm{Lo} = \mathrm{DOC} \times \mathrm{DOCf} \times 16/12 \times \mathrm{MCF} \quad (3)$$

where Lo is a potential methane generation capacity (kg/tonne), MCF is a Methane correction factor (fraction; default =1.0), DOC is a Degradable organic carbon (kg/tonne), DOC$_f$ is a Fraction of assimilated DOC (IPCC,1996 default = 0.77; IPCC, 2006 default = 0.50), F is a Fraction of methane in landfill gas (0.5 default), and 16/12 is a Stoichiometric factor.

3. MATERIALS AND METHODS

In the present study, the methane generation estimates from Land GEM model were compared to the methane recovery rates for areas A and B in Kahrizak landfill, adding a 20% loss factor, for determining the accuracy of the models. In order to undertake this analysis, the following steps were undertaken:

Modeled results need to be compared with methane recovery rates, taking into consideration gas recovery efficiency, to ensure accuracy [21]. Gas recovery efficiencies are typically estimated to be in the range of 60–90%, based on measured gas recovery rates divided by modeled gas generation rates [22,23]. As a result of the mass balance work done by Spokas et al. [21] , the French environment agency adopted the default percent recovery values of 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geo membrane final cover and active LFG recovery. The US EPA (2004) applies a default gas recovery rate of 75% [24].

3.1. Kahrizak landfill site and the basic data

Kahrizak Landfill is located 25 (km) south of Teheran, at the vicinity of the old Tehran-Qom road. Currently, Kahrizak receives all the municipal solid wastes and hospital wastes generated in Teheran. The land-filling operation in Kahrizak started around 1970. The average quantity of wastes disposed at the site today is approximately 7000 (Tons/day). In order to estimate the landfill gas generation through landfill gas models, it is necessary to collect information pertaining to the amount, location, and time of placement for the incoming wastes during the history of the landfill operation. The general layout for the facility is shown in Figure 1. The layout shows six main areas in which waste was disposed of since the establishment of the Kahrizak Landfill. The areas are categorized as followings: Wood Area 1, Wood Area 2, and Areas A, B, C, and D. It could be deducted from site investigations, that it would be practical and economically feasible to extract landfill gas only from Areas A and B. From 1992 until 1994, the Area A was used for placing wastes. Area A was later used for land-filling from the 2000 until 2002. Area A, which is located in the northern section of the landfill site is close to a private cardboard recycling factory. This recycling factory is a potential end-user of the landfill gases in its manufacturing process. From 1998 until 2001, the trench method was also used in Area B. Area B was again used from 2002 until 2004. A summary of the landfill operation in the Areas of A and B is shown in Table 2. The annual waste input will be subsequently used in that gas calculation in the following section.

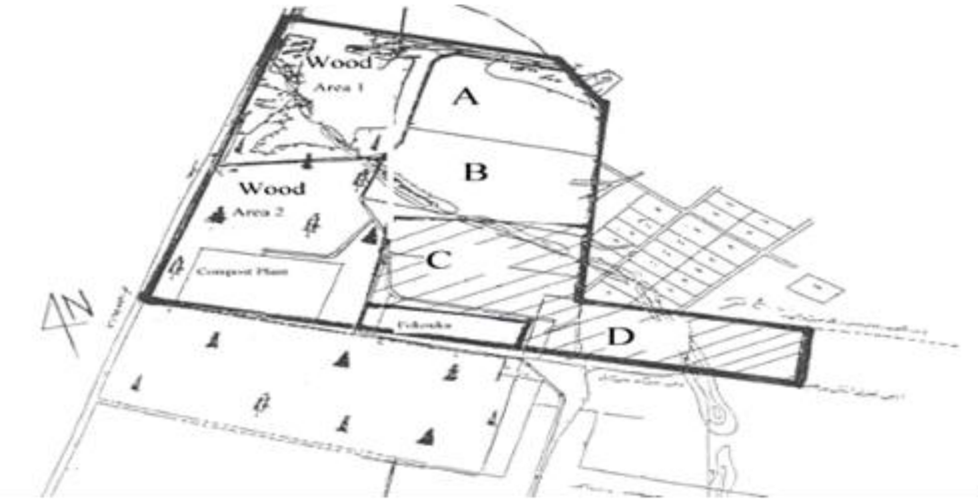

Fig .1. Layout of the Kahrizak Landfill

Table 2. Annual Waste Input from 1992 to 2004 (in Million tons) [25].

Year	Incoming Wastes	A	*B*
1992-93	2.23	2.23	
1993-94	2.33	2.33	
1994-95			
1995-96			
1996-97			
1997-98			
1998-99	2.25		*2.25*
1999-2000	2.21		*2.21*
2000-01	2.24	1.12	*1.12*
2001-02	2.42	2.42	
2002-03	2.53		*2.53*
2003-04	2.58		*2.58*
2004-Sep. 04	1.97		*1.97*
Total	*20.8 Million Tons*	*8.10*	*12.66*

Table 3 represents wastes that are typically transported from the transfer stations in Tehran to the Kahrizak Landfill. The ‘Wet waste’ comprises food waste, peels, meats, etc. – all typically biodegradable wastes. As illustrated in Table 2, about 70% of Tehran wastes materials are organic materials specially food residues which decompose quickly and produce gas.

Table 3. Waste characteristics of the Kahrizak landfill site [25]

Waste Type	***Mass (%)***	***Volume (%)***
Wet waste	67.8	*26.4*
Bread	1.0	*2.7*
Soft plastic	2.2	*14.8*
Hard plastic	0.6	*4.0*
PET	0.7	*9.7*
Plastic bags	6.2	*16.8*
Paper	4.4	*4.0*
Paper	3.7	*5.1*
Ferrous metals	1.6	*1.1*
Non-ferrous metals	0.2	*0.1*
Fabric	3.4	*9.4*
Glass	2.4	*2.2*
Wood	1.7	*1.5*
Tires	0.7	*0.6*
Leather	0.6	*0.4*
Dust & Rubble	1.3	*0.6*
Special Waste (Health Care Waste)	*1.6*	*0.7*

Waste Volumes & Disposal Rates: Approximately 2.0 million tons of waste per year is delivered to the site. The landfill volume of Area A is some 8.10 million cubic meters, and for the Area B is 12.66 cubic meters. It is considered that only Areas A and B will be used for installation of the landfill gas extraction system, as the depths of buried solid waste on the remainder of the Kahrizak site are too shallow for cost efficient landfill gas recovery. Thus, it is anticipated that the total waste volume of buried solid waste is some 20.8 million cubic meters from where a sustainable yield of landfill gas could practically be extracted.

- **Waste Areas and Depths:** Area A is approximately 55 hectares in size, with waste depths ranging from 10m to 50m. The area was land-filled using a ‘trenching method’, which consists of large excavations, approximately 100-300 meters long, 20-25 meters in depth, and 40-60 meters in width. During the past 2 years, a layer of waste was placed over Areas A and B to an approximate depth of 10 meters. This would indicate a total depth of 35m and the Area B is approximately 65 hectares.
- **Moisture Content of Dumped Wastes*:*** Moisture content tests of waste streams delivered to Kahrizak have a range of 65 – 70%.

- **PH of the Landfill*:*** Area A would appear to display a pH value of 7.3 to 7.4, whilst for area B the pH value is approximately 6.0 to 6.8. However, the high variance in age of the waste layers disposed in these areas complicates these assumptions.
- **Climatic Situation*:*** The approximate annual rainfall is 240mm, the annual average temperature is approximately 18 ^{o}C., the evaporation rates are estimated as 2,500mm per annum, the humidity ranges from 16% in the summer months to 57% in the winter, and the average is about 32%.
- **Waste Temperature:** Unknown, but gas temperature appears to range from 35 to 45 ^{o}C.
- **Elevation:** 1020 to 1060 meters above the mean sea level.

Gas production rate and biological processes of the dumping area are on the basis of temperature rate and humidity percentage. These two factors are vital for the bacterial growth and metabolism. Transference of food waste and bacteria is also crucial. In addition, temperature and humidity rates are influencing on the gas production of dumping areas.

4. Results and discussion

The LandGEM model version 3.02, was utilized to estimate emission rates for methane and carbon dioxide from the Kahrizak Landfill for up to 200 years after closure. The calculations were concentrated on Areas A and B, which would lead the largest potential of gas emissions. Table 4 indicates the input data for running the LandGEM model for Kahrizak landfill and the LandGEM Model results of equivalent carbon calculation for Areas A and B are presented in Table 5.

Table 4. Input review for Kahrizak landfill

Landfill Characteristics			
Landfill Open Year	1992		
Landfill Closure Year (with 80-year limit)	2004		
Actual Closure Year (without limit)	2004		
Have Model Calculate Closure Year?	No		
Waste Design Capacity	21,370,000	mega grams	
Model Parameters			
Methane Generation Rate, k		0.050	*year*$^{-1}$
Potential Methane Generation Capacity, L_o		100	m^3/Mg
NMOC Concentration		4,000	*ppmv as hexane*
Methane Content		*61*	*% by volume*

Table 5. Land GEM Model results for Areas A and B in (Equivalent Carbon in Tons)

Areas A and B Equivalent Carbon in Tons	
Year	**tCO2/year**
2005	1,382,535
2006	1,315,356
2007	1,251,117
2008	1,190,112
2009	1,132,047
2010	1,076,775
2011	1,024,296
2012	974,316

Note: A collection efficiency of 70% was used in the above calculation.

The amounts of CH_4, CO_2, and NMOC gas emission in Kahrizak Landfill were calculated and the results are shown in Table 5 based on Land GEM model and input parameters. As illustrated in Figure 2 and 3, the highest amounts of methane and carbon dioxide emissions from Kahrizak Landfill in 2005 were 7.66×10^4 Ton/year and 1.34×10^5 Ton/year respectively.

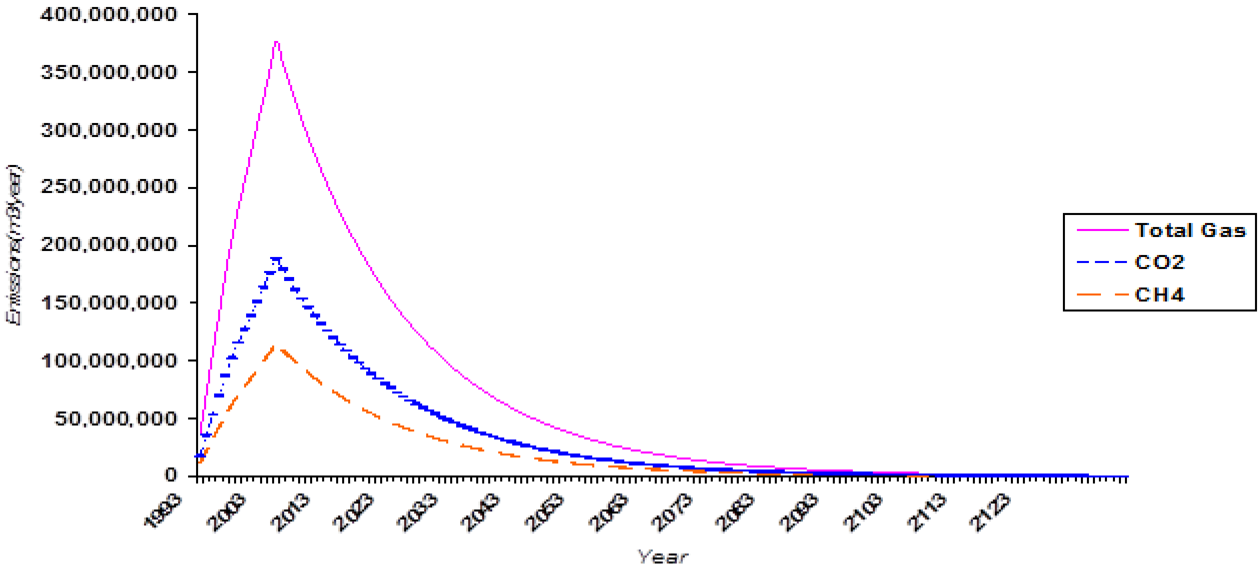

Figure 2. Prediction of CH4 and CO2 emissions in Kahrizak landfill (k=0.02)

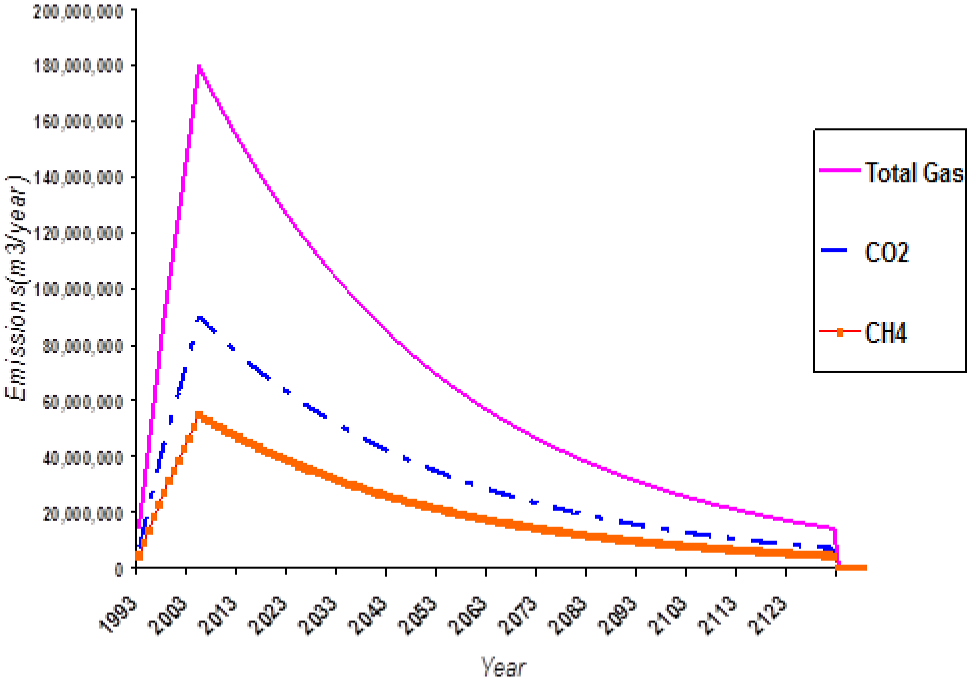

Figure 3. Prediction of CH4 and CO2 emissions in Kahrizak landfill (k=0.05)

Kahrizak landfill is located in a dry place with less than 635 mm annual precipitation. According to Clean Air Rule, the proposed amount of k for traditional dumping landfills is 0.05. The components of waste materials are one of the influencing factors on methane production rate and its spread. The consumption pattern of Iran is quite different from that of the other countries. LandGEM 3.02 model consistently produced estimates for prediction of CH4 and CO2 emissions lower (about 10 %) (Figure 4) than the actual gas recovery rates. The results of the mathematical model demonstrated a significant amount of gas production in the first years of dumping in Kahrizak landfill. Methane and carbon dioxide emissions in Karaj and Shiraz landfills were calculated as well as Kahrizak, through using LandGEM model. The results are as follows: in Kahrizak landfill methane and CO2 emissions are 7.66×10^{4} Ton/year and 1.34×10^{5} Ton/year, in Karaj landfill 1.34×10^{5} Ton/year and 2.36×10^{5} Ton/year, and in Shiraz landfill 7.358×10^{3} Ton/year and 3.81×10^{4} ton/year, respectively. The results are demonstrated in Figures 5 and 6.The comparison of CH4 and CO2 emissions among Kahrizak, Karaj and Shiraz landfills demonstrated that Karaj landfill has the highest amount of methane emission, Shiraz landfill is second and Kahrizak landfill has the least amount of LFG emission due to CH4 and CO2 recovery operations that have been started in the site since 2005.

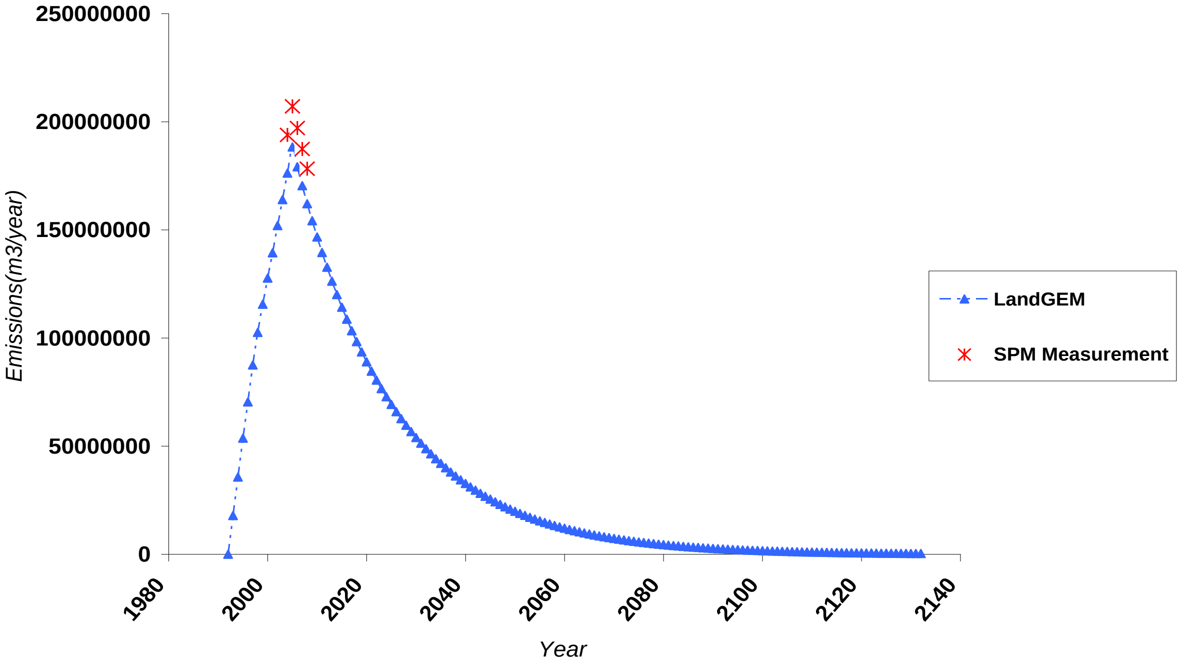

Figure 4. Comparison of predicted CH4 and CO2 emissions the actual gas recovery rates with Land GEM

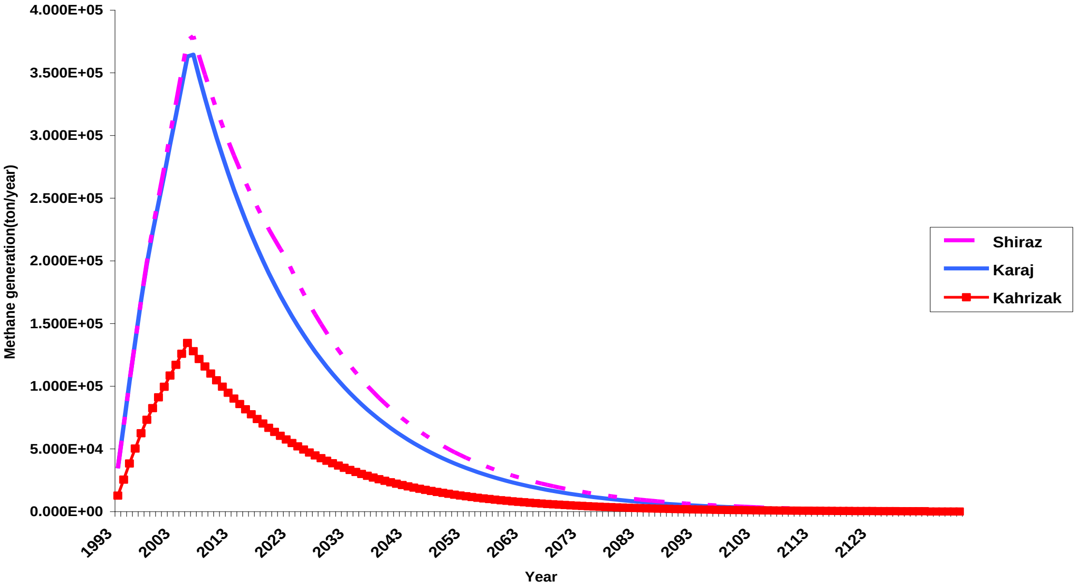

Figure 5. Comparison of predicted CH4 emission in Kahrizak, Shiraz and Karaj landfills

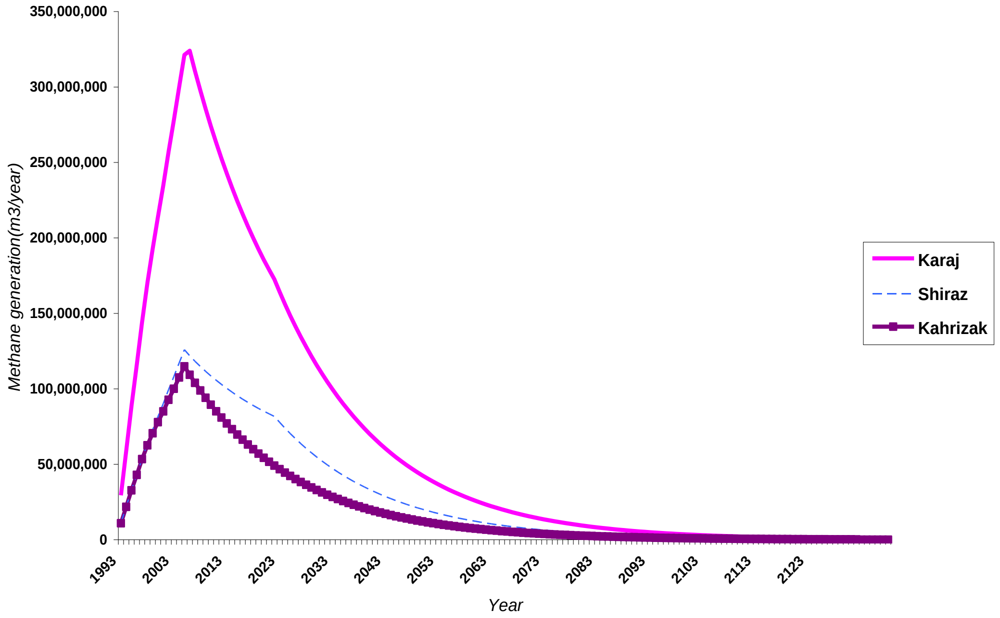

Figure 6. Comparison of predicted CO2 emissions in Kahrizak, Shiraz and Karaj landfills

The sensitivity analysis for various quantities of k (methane production rate) has demonstrated that any increase in the amount of k will result in methane emission increase from the dumping sites. Moreover, during the first years of dumping in landfills, a significant amount of methane will be produced which, in case of prompt recovery method, will control a considerable amount of atmospheric and environmental pollutions. The result is demonstrated in Figure 7.

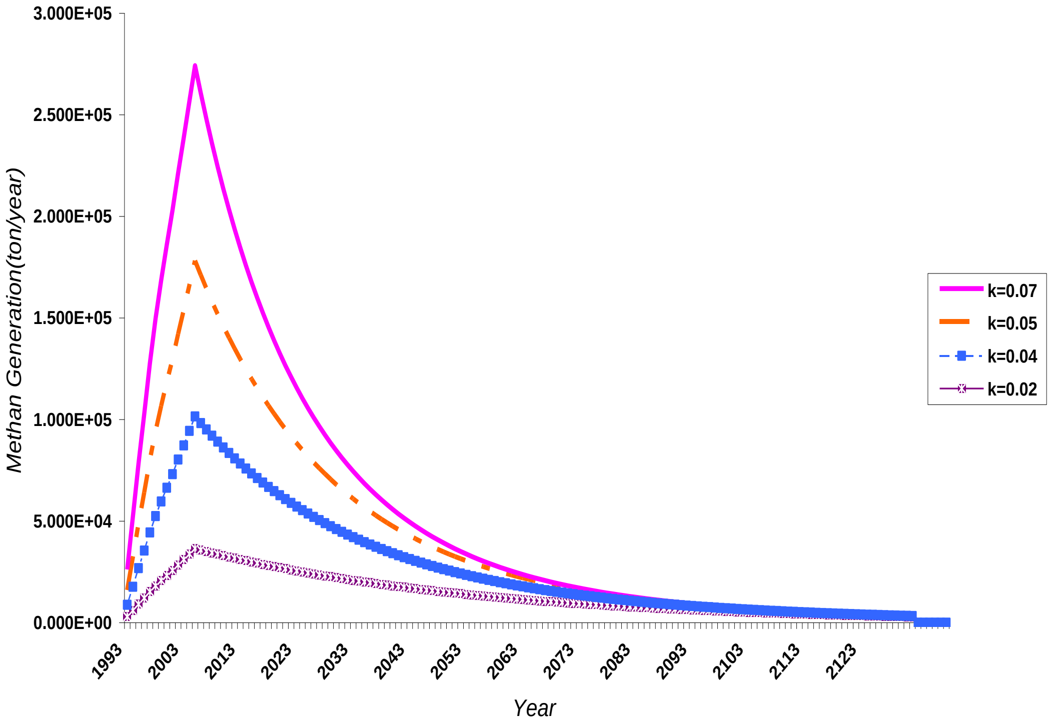

Figure 7. Sensitivity analysis for CH4 emissions with different quantities of k

5. Conclusion

This study is the first of its kind to compare modeled CH4 and CO2 generation to CH4 and CO2 recovery rates of the Kahrizak landfill. Through the use of Land GEM model, CH4 and CO2 emission rates and the sensitivity analysis were calculated for 1992 to 2132 for Kahrizak , Karaj and Shiraz landfills. Land GEM 3.02 model consistently produced estimates for prediction of CH4 and CO2 emissions lower (about 10 %) than the recovery rates The results are in agreement with the results of Tompson [14]. The results of the mathematical model also demonstrated a significant amount of gas production in the first years of dumping in Kahrizak landfill. Considering that defaults or provincial rates were applied for landfill gas concentration, decay rates and DOC, rather than site-specific data, the results for Land GEM are fairly good. While this analysis presumes that Land GEM model considers the important factors in determining LFG generation, other factors could be impacting LFG generation, including depth of landfills, temperature, and waste density [26]. The value of k is a function of the refuse moisture content, availability of the nutrients for methanogens, pH, and the temperature. The value of k obtained from the data collected for the emission guidelines ranges from 0.003 to 0.21 [24]. For wet climates (greater than 25 in. of rain per year), k=0.05. Although many different environmental conditions act upon decay, typically only precipitation is considered to have an effect on k [24,27,4], Moisture is essential for bacterial growth, metabolism, and nutrient transport. For dry climates, k=0.02. The EPA default value of k is 0.05 1/yr. Sensitive analysis for CH_4 emissions with different quantities of k has been done. The higher the value of k, the faster the methane generation rate increases and then decays over time. Tehran waste materials are dumped directly up to 92%. In such a condition, greenhouse gases production-rate is about 17,836,079 tons of carbon dioxide equivalents and the consumed energy is 9.2×10^9 million joule annually in the country. By gas recovery and extracting energy with the efficiency of 75 percent from landfills in the country, the generation rate of greenhouse gases will reduce to around 557,633 tons of CO_2 equivalent. In case of gas recover and burning of gases, the emission rates of greenhouse gases will reach 2,929,150 tons equivalent to carbon dioxide and the energy consumption will be 372,252 BTU more than the afore-mentioned energy consumption. Through gas energy recovery and burning it, greenhouse emission rate will decrease to 3 million tons of CO2 equivalent. Furthermore, gas recovery from waste materials of landfill could be used to generate electricity and apply in fuel cell technology and combined heat and power generation (CHP) results in dramatic decrease in carbon dioxide emission rate and increase in fuel efficiency and generate revenue by the sale of emission reductions.

NOMENCLATURE

Q	Methane production (kt/yr)
M	Waste generation (Mt/yr)
DOC	Degradable organic carbon (kg/tonne)
DOC_f	Fraction assimilated DOC
F	Fraction of methane in landfill gas
D	Collection efficiency factor
Q	Methane production (kTone/yr)
DOC	Fraction of assimilated DOC
M	Waste generation (Mt/yr)
DOC	Degradable organic carbon (kg/Tone)
k	Decay rate (yr^{-1})
T	Time of waste disposal (yr)

Q	methane production (kt/yr)
M	waste generation (Mt/yr)
k	decay rate (yr^{-1})
Lo	methane generation potential (kg/tonne)
t	time of waste disposal (yr)
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^{-1})
L_0	potential methane generation capacity(m^3/ton)
M_i	mass of waste accepted in the ith year (ton)
t_{ij}	age of the jth section of waste mass M_i accepted in the ith year
A	fraction of municipal solid waste (MSW) that is paper and textiles waste
B	fraction of MSW is the garden or park waste
C	fraction of MSW is food waste
D	fraction of MSW is the wood or straw waste
X	annual average precipitation
MCF	Methane correction factor

Conflict of Interest

"The authors declare no conflict of interest".

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