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Modelling and assessment of landfill gas generation at Erzurum municipal landfill site by LandGEM

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Abstract
Landfill areas have always been a common application for municipal solid waste management. However, land use problems, environmental pollution and increasing recycling implements have limited the amount of solid waste which is stored in the landfill areas. Despite all disadvantages, it is still considered a preferred disposal method fort he solid waste, especially when methane gas released from the areas is used to obtain electrical energy. In this context, the aim of this study is to estimate the landfill gas amounts originating from the Erzurum Solid Waste Landfill area using the LandGEM 3.02 version developed by EPA and to compare it with the methane gas concentrations measured on-site for the last three years. Total landfill gas, methane, carbon dioxide, and NMOC amounts were estimated with the model by choosing the basic parameters of the LandGEM (*k* and *Lo* values) according to the Clean Air Act and AP-42 inventory suggested by the EPA. The amount of the same gases was also predicted by manually calculated the *k* and *Lo* values (User Specified) with the specific data of the field. Finally, the amount of landfill gases obtained by using all three inventories (the Clean Air Act, AP-42 and User Specified) was compared with the methane concentrations measured in the field in order to confirm the model results. First result is that the methane gas concentrations predicted by the model were nearly close to the real methane measurements on site. Secondly, the operating period determined as 20 years for Erzurum landfill area when it was put into operation in 2008, while it was estimated as 23 years according to the LandGEM model results. Erzurum Solid Waste Landfill area has already been designed for power generation and the energy is produced at present. Therefore, the model can easily be used and verified for future improvement of the landfill area and the prediction of the amount of the energy obtained from the wastes.

Keywords
Landfill Gas, LandGEM, Energy recovery, Methane generation, Solid Waste

Introductıon

In the 1980s, a sustainable development model was adopted in the economy, and over time, different disciplines such as society, urbanization, environmental management, and ecology began to deal with the sustainability approach. The notion of sustainable solid waste management (SWM) has emerged with the determination of convenient disposal methods by considering the costs to protect and improve resources, to minimize all environmental risks, and to see waste as a resource (Akdoğan ve Güleç, 2007; Bilgili 2002). Effective use of resources forms the basis of sustainability and, recycling, energy generation from the incineration and compost production are also practices that compose sustainability in solid waste management. According to this sustainable solid waste management, while the prevention of waste generation is the most preferential option; disposing waste in landfill should be evaluated as the least preferred option (EU 2021).

Considering the average daily solid waste quantity in EU member countries was 1.375 kg per capita in 2019, about 225 million tons of municipal waste were produced in total. About half of these wastes was recycled, while 23% was disposed in landfills.

However, in some EU countries more than 60% of waste is still sent to landfills, while it was 53.6% in US in 2011 (EC, 2021; USEPA, 2011). In the case of our country, the average daily amount of municipal waste was calculated as 1.16 kg per capita, 32.2 million tons of solid wastes were collected by municipalities, and 67.2% of the waste was sent to landfills in Turkey (TÜİK, 2018), which almost equals to the ratio of that disposed in landfills or open dumps all over the world (ÇYGM, 2017).

The anaerobic degradation of solid wastes in the landfill area results in the production of landfill gas (LFG) which represents primarily greenhouse gas (GHG) consisting mainly of methane (CH_4; 50-60%) and carbon dioxide (CO_2; 40-50%). Besides CH_4 and CO_2, LFG is composed of other unimportant gases, such as nitrogen (N_2), hydrogen sulfide (H_2S), and nonmethane organic compounds (NMOCs; 5%). GHG emission ratio usually depends on the organic fraction of solid waste because the various types of organic wastes have a different degradable organic carbon (DOCs). Therefore, emission ratio depends on waste composition, waste compaction, the degradable organic fraction, leachate recirculation and the other environmental factors (Mokhtari et al., 2020; Osra et al., 2021; Hosseini et al., 2018).

Among these gases, CH_4 is one of the most important greenhouse gases that have a 28 times higher global warming potential than CO_2, and the landfills account for 18% of global anthropogenic CH_4 emissions where require the taking measures that limit the release of methane into the atmosphere. Therefore, it is very important to model and estimate the methane gas production rate at the landfill areas in the case of landfill gases recovered for the energy. Landfill gas is also specified as “clean renewable energy sources” in the EU directive 2009/28/EC (Şentürk et al., 2020; Rahman et al., 2021; Fallahizadeh et al., 2019).

It is feasible to identify LFG emissions by evaluating LFG flows and composition in test wells at the active landfill sites and obtaining more exact results about the production of LFG, but it is considered a time-consuming and economically unfeasible. Therefore, different mathematical models have been developed for the aim of predicting LFG production and recovery based on previous and/or future waste amounts for different climatic zones due to the complicated structure of landfill gas formation. Furthermore, it is very important to define the most appropriate model and the parameters for the field to make correct predictions. Among different LFG prediction models, Intergovernmental Panel on Climate Change (IPCC) Model and Landfill Gas Emission Model (LandGEM) have been mostly used in former studies for predicting landfill methane emissions produced through the anaerobic decomposition of the waste (Andriani et al., 2019; Lattanzi et al., 2019). LandGEM model is based on a first-order decomposition of the waste and specifically developed by the US. Environmental Protection Agency for determining the methane generation for inventory. Therefore, methane generation rate, *k*, is the main parameter and determines the propotion of methane generation for the mass of waste in the landfill. According to LandGEM model, the higher the value of *k*, the faster the methane generation ratio increment and then decays over time. The methane generation ratio is mainly a function of four factors which are humidity content of the waste mass, availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide, pH and temperature of the waste mass. The default methane generation rate values are based on Clean Air Act (CAA) Defaults and Inventory Defaults of Compilation of Air Pollutant Emission Factors (AP-42) for the conventional landfills in the LandGEM model. It can also be calculated with the specific parameters of any landfill area which is named under User Specified values. The other important parameter for LandGEM model is the potential methane generation capacity depending only on the type and composition of waste deposited in the landfill (USEPA, 2005).

Therefore, the present study aims to estimate the amount of landfill gases (total landfill gas, methane, carbon dioxide and NMOC amounts) and energy equivalent by using the LandGEM model fitted for gas emission in the municipal landfill area in Erzurum City for a 41-year period from 2008 to 2049. Landfill gas energy recovery is conducted via a biogas plant operated in the area having the measurments of real CH_4 concentration on-site. Therefore, the accuracy of the model predictions was studied to compare by the difference between the predictions of model results and real gas emissions measured on-site for the last three years.

Materials and Method

Description of the study area and context

Erzurum Metropolitan Municipality landfill area is located in Aziziye District of Erzurum City (Figure 1). LandGEM software was used to estimate the methane rate produced in the area. The area has been served since May 2008. Within the scope of the project, the waste deposition area consists of 3 sites. Surface area of first lot is 6 ha, the 2nd lot is 5 ha, and the 3rd lot is 6.64 ha. Filling of the first lot has been completed and was temporarily covered in July 2017. The storage capacity is 800,000 m^3 for the first lot, 900,000 m^3 for the second lot and 1190,000 m^3 for the third lot (Hunce et al., 2012). According to data obtained from Erzurum Metropolitan Municipality, the daily amount of solid waste sent by district municipalities (Aşkale, Aziziye, Palandöken, Yakutiye) is approximately 360 tons/day in 2019.

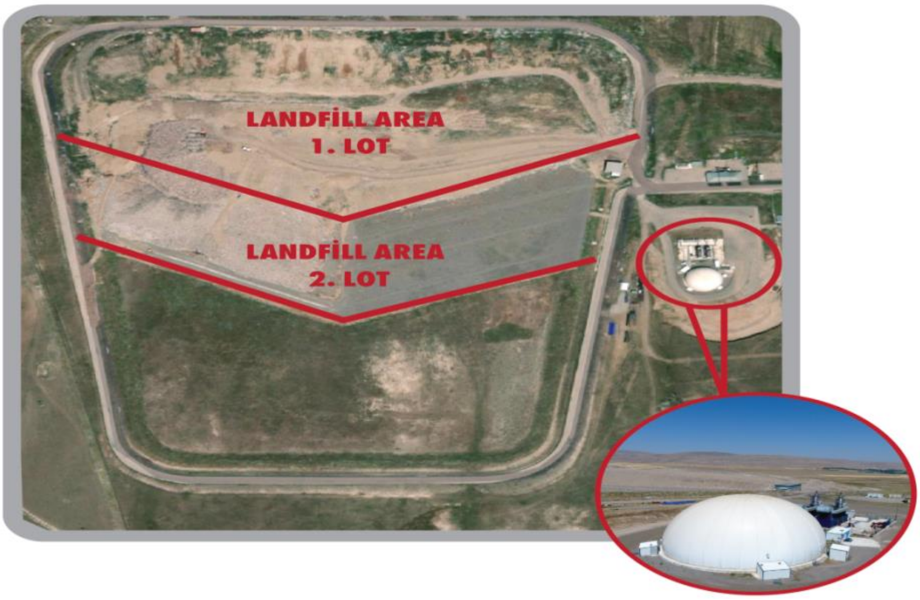

Figure 1. Study area: Erzurum Metropolitan Municipality Landfill.

Characterisation of the Waste Accepted in Landfill

The characterization of Erzurum Metropolitan Municipality solid wastes is shown in Table 1. Data are provided from Zero Waste Management System Plan 2020 prepared by Provincial Directorate of Environment and Urbanization Erzurum (Anonim, 2020). Considering the waste characterization statistics of Turkey, the ratio of biodegradable waste of solid waste (56.94%, w/w) in Erzurum City is very close to the national waste characterization average (55.54%, w/w) (TÜİK, 2018). These biodegradable wastes, which constitute more than half of the wastes, will be disposed of in the landfills unless an effective waste separation infra-structure is established. Therefore, the energy production from LFG is still of great importance for the Erzurum landfill area.

Table 1. Waste characterization of Erzurum landfill area.

Waste Characterization		Amount, %	Total
Recyclable Wastes	Paper	2.69	22.37
	Cardboard	4.72	
	Plastic	10.69	
	Glass	2.96	
	Metal	1.31	
	Waste Electricity and Electronic Equipment	1.1	
	Dangerous Waste	0.92	
Other Wastes	Other Non-combustibles	7.0	20.69
	Other Combustibles	11.5	
	Other	0.17	
Biodegradable Waste	Kitchen Waste Park and Garden Waste	56.94	56.94

Description of the LandGEM Model

LandGEM is a software application with a Microsoft Excel interface that predictions air pollutants and other gases from municipal solid waste (MSW) landfills developed by the U.S. Environmental Protection Agency (USEPA, 2005). LandGEM is based on first order degradation of solid waste in MSW landfills for estimating emission rates of total landfill gas, methane, carbon dioxide, nonmethane organic compounds (NMOCs), and some other air pollutants. LandGEM can use either site-specific data to prediction emissions or default parameters if no site-specific data are available. LandGEM contains two sets of default parameters which are CAA Defaults and AP-42 inventories. LandGEM uses the following first-order decomposition rate equation (Eq. 1) to prediction annual emissions over a specified period that the user chooses:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] e^{-kt_{ij}} \quad (1)$$

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 ($year^{-1}$), *Lo*, potential methane generation capacity (m^3/Mg), M_i, mass of waste accepted in the i_{th} year (Mg), t_{ij}, age of the j_{th} section of waste mass Mi accepted in the i_{th} year (decimal years, e.g., 2.3 years).

The model parameters, *k*, determines the rate of methane generation for the waste mass in the landfill. The higher the value of *k*, the faster the methane generation rate increases and then decays over time. The value of *k* is primarily a function of four factors; moisture content of the waste mass, availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide, pH of the waste mass, and temperature of the waste mass. The other parameter of the model, *Lo*, depends only on the type and composition of waste placed in the landfill. The higher the cellulose content of the waste, the higher the value of *Lo*. The default *Lo* values used by LandGEM are representative of MSW. In this study, Erzurum landfill area is classified as conventional landfill category of which the moisture content is accepted as 40-60% and accordingly, *k* and *Lo* value is chosen as used to the conventional landfills for both CAA and AP-42 standards in the model. Additionally, *k* and *Lo* values are calculated by manually using specific information of Erzurum landfill area like waste content, precipitation etc. The equation used for the manuel calculation of *k* and *Lo* defined as User Specified parameters is shown in between Eq (2-6). The User Specified *Lo* is calculated as;

$$Lo = MCF \times DOC \times DOC_f \times 16/12 \times f \quad (2)$$

where; MCF, methane correction factor (1=well managed landfill), DOC, degradable organic carbon (fraction), DOCf, fraction DOC dissimilated, f, methane fraction by volume (%), 16/12, the ratio of molecular weight of CH_4/C (Osra et al., 2021) . The site-specific degradable organic carbon (DOC) is calculated based on IPCC (1996) formula (Huang et al., 2022);

$$\%DOC \text{ (by weight)} = 0.4(A) + 0.17(B) + 0.15(C) + 0.3(D) \quad (3)$$

where; A, % of paper and textile of municipal solid waste, B, % of garden-park waste, or other non-food organic matters, C, % of food waste, and D, % of wood or straw waste. DOCf can be determined through the lignin content of the volatile solid (VS);

$$DOC_f = 0.83\text{-}0.028 \times LC \quad (4)$$

where; 0.83 and 0.028, empirical constant, and LC, lignin content of the VS expressed as a percent of dry weight from leachate sample. DOCf is also calculated by equation:

$$DOC_f = 0.014 \times T + 0.28 \quad (5)$$

where; *T*, the mean temperature of landfill sites mainly accepted as 35 °C (Yıldırım, 2020; Brito et al., 2021). It is possible to calculate the *k* value for a waste mass based on precipitation rates. The manuel calculation of *k* value is shown in Eq (6);

$$k = (3.2 \times 10^{-5} \times \text{annually precipitation (mm)}) + 0.01 \quad (6)$$

In this Eq (6), the annually precipitation is accepted as 433 mm according to meteorological condition of Erzurum City (Şentürk, 2020; Yıldırım, 2020).

Finally, the values of *k* and *Lo* were used as default model parameter obtained by two sets of default parameters of CAA and AP-42. Additionally, these parameters were calculated by using the Equations (2-6) to be able to make a comparison between default model parameters of CAA and AP-42 and calculated parameters of *k* and *Lo* named as User Specified parameters based on the specific data of the area.

Results and Discussion

In the first part of the study, the total landfill gas, CH_4, CO_2 and NMOC amounts were determined by LandGEM Model for Erzurum Municipality Solid Waste Landfill Area since 2008 which was the opening year of area until the end of 2020. The area closing year was set as 2028 when the project was taken into operation in 2008. Therefore, the closure year of the landfill area is going to be 2028 according to the project. LandGEM model was going to use the calculation of the closure year of the area as well to compare project year and model year. Therefore, the calculation part of the closure year, which was also determined as the LandGEM model default, was accepted as NO. In this case, another important model input parameter for the LandGEM model is the Waste Acceptance Rate of the landfill area. For this purpose, the amount of solid waste accepted to the landfill area from 2008 to 2020 (including 2020) obtained by Erzurum Municipality was also used as model second important input. The LandGEM model calculates the Waste Acceptance Rate by using these data on by own.

Accordingly, all parameters used as LandGEM model inputs are submit in Table 2. The total landfill gas, CH_4, CO_2 and NMOC amounts were calculated in two different ways by taking the values in both CAA and AP-42 standards, which are the two default model parameters for the LandGEM. In the first case, the methane formation rate (*k*) and the methane formation capacity (*Lo*) were determined as the values of 0.05 $year^{-1}$ and 170 m^3/Mg for the CAA standards; and 0.04 $year^{-1}$ and 100 m^3/Mg values for AP-42 standards respectively. Since NMOC amount were not measured at the landfill area, this parameter was accepted 4000 and 600 ppmv (in hexane) determined for the CAA and AP-42 standards, respectively for the situation where there is no disposal with hazardous waste (Karayılan, 2018). Finally, methane content was chosen as %50 from model defaults for both CAA and AP-42 standards, while it was used as %52 for the calculation of User Specified standards.

Other than the CAA and AP-42 standards used as LandGEM model defaults, *k* and *Lo* values which were calculated manually using the data collected from area according to Equation between (2-5). Table 2 summarizes all these values as taken from the model metadata.

Table 2. LandGEM Model Parameters for estimating the total landfill gas, CH_4, CO_2 and NMOC of Erzurum Municipality Solid Waste Landfill Area between 2008-2020

Landfill Characteristics	CAA	AP-42	User Specified
Landfill Open Year	2008	2008	2008
Landfill Closure Year *(with 80-year limit)*	2028	2028	2028
Actual Closure Year (without limit)	2028	2028	2028
Have Model Calculate Closure Year?	NO	NO	NO
Waste Design Capacity	-	-	-
Methane Generation Rate, *k* *(*$year^{-1}$*)*	0.050	0.040	0.024
Potential Methane Generation Capacity, L_o *(*m^3*/Mg)*	170	100	42
NMOC Concentration *(ppmv as hexane)*	4,000	600	4,000
Methane Content *(% by volume)*	50	50	52

In the second part, the Model Closure Year calculation was selected as YES to validate the project closing year (2028) with the LandGEM model, which has a 20-year operational life (2028) in the project reports of Erzurum Province Solid Waste Landfill Facility. Therefore, Waste Design Capacity needed for the closure year calculation was obtained as 2,836,000 megagrams from the project reports. In this case, there is no need to enter the amount of solid waste accepted to the landfill area as model input, because the model is going to ignore that. Then, the methane formation rate (*k*) and the methane formation capacity (*Lo*) for three cases shown in Table 2 were also used as LandGEM model inputs presented in Table 3 for this case. As can be seen from Table 3, the LandGEM model has calculated the Closure Year of landfill area as 2031 for all three standards. This value is very close to the year 2028, which was determined during the project design period of the landfill area. Therefore, LandGEM model represents that the landfill area can accept waste for 3 more years after 2028.

Table 3. LandGEM Model Parameters for estimating the total landfill gas, CH_4, CO_2 and NMOC of Erzurum Municipality Solid Waste Landfill Area between 2008-2020 including Model Closure Year calculation.

Landfill Characteristics	CAA	AP-42	User Specified
Landfill Open Year	2008	2008	2008
Landfill Closure Year *(with 80-year limit)*	2031	2031	2031
Actual Closure Year (without limit)	2031	2031	2031
Have Model Calculate Closure Year?	YES	YES	YES
Waste Design Capacity *(Mg)*	2,836,000	2,836,000	2,836,000
Methane Generation Rate, *k* *(*$year^{-1}$*)*	0.050	0.040	0.024
Potential Methane Generation Capacity, L_o *(*m^3*/Mg)*	170	100	42
NMOC Concentration *(ppmv as hexane)*	4,000	600	4,000
Methane Content *(% by volume)*	50	50	52

The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated by using CAA, AP-42 and User Specified standards as the LandGEM model data inputs both NO and YES situations are shown in Figure 2-13 as megagrams (Mg/year). First, Figure 2a and 2b show the amount of the total landfill gas, CH_4, CO_2 and NMOC values as in annual me-gagrams (Mg/year) for both NO and YES situations obtained by the calculation with CAA standards as the LandGEM model default in Erzurum Province Solid Waste

Landfill area. According to Figure 2a, total landfill gas and methane were predicted as 3.237x10^4 and 8.647x10^3 Mg/year, respectively at the real closure year of the landfill area which is 2028. On the other hand, these gases were predicted as 3.501x10^4 and 9.352x10^3 Mg/year, respectively at the model closure year of 2031 in Figure 2b. According to LandGEM model, landfill area is going to accept solid wastes three more year than the actual closing year of the landfill. Therefore, the increased amount of total landfill gas has come from the difference between the model closure year (2031) and landfill real closing year (2028). It will be possible to produce landfill gas three more year to generate power which provides to contribution all power generation.

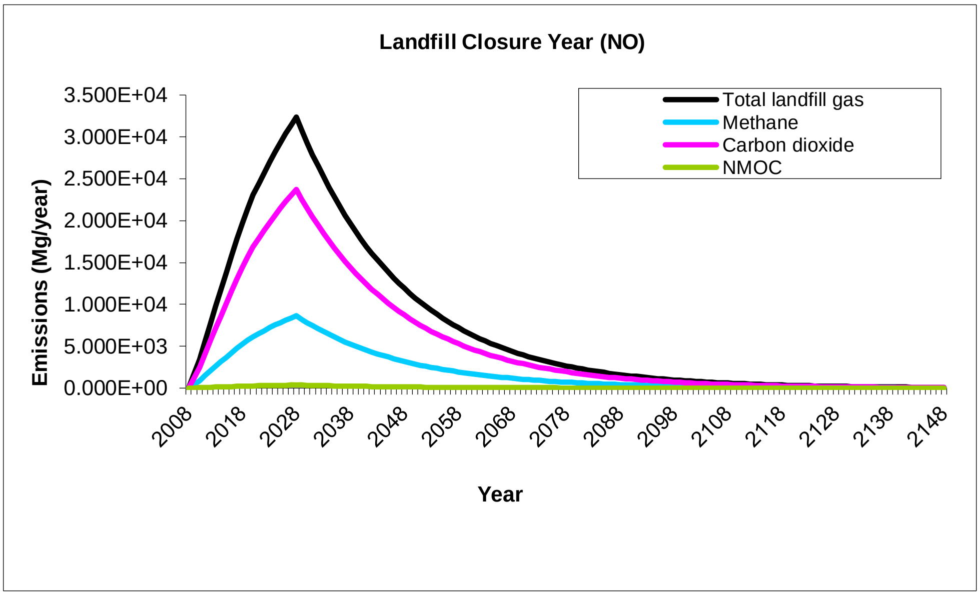

Figure 2a. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with CAA stan-dards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area for the years between 2008 and 2020 (Mg/yıl, Model Closure Year=NO).

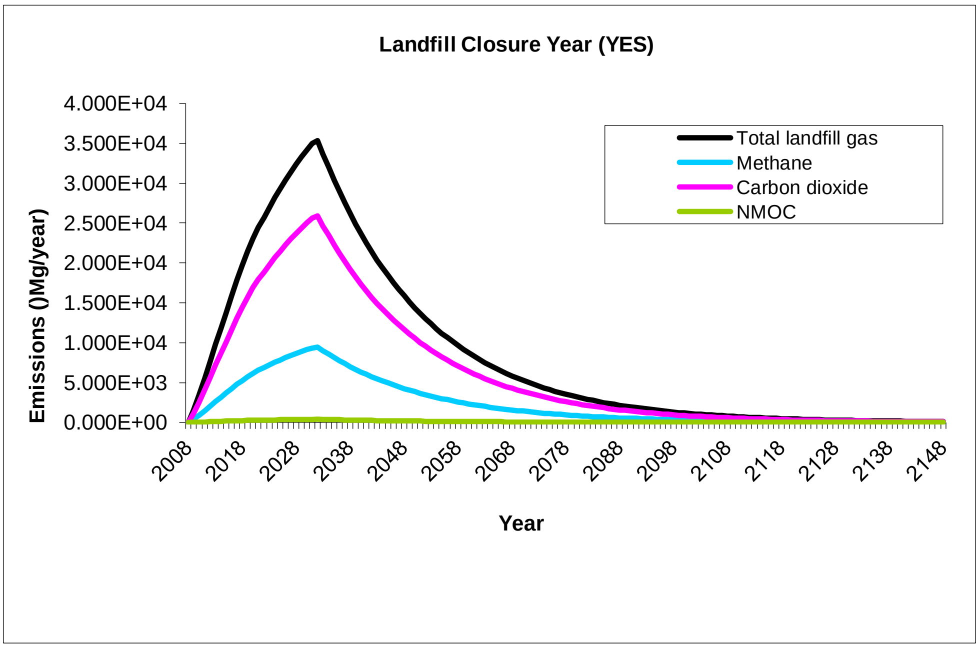

Figure 2b. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with CAA standards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area (Mg/yıl, Model Closure Year=YES).

Figure 3a and 3b depict the amount of the total landfill gas, CH_4, CO_2 and NMOC values in annual megagrams (Mg/year) for both NO and YES situations obtained by the calculation with AP-42 standards as the LandGEM model default in Erzurum Province Solid Waste Landfill area. According to Figure 3a, total landfill gas and methane were predicted as 1.655x10^4 and 4.420x10^3 Mg/year, respectively at the real closure year of the landfill area which is 2028. On the other hand, these gases were predicted as 1.809x10^4 and 4.831x10^3 Mg/year, respectively at the model closure year of 2031 in Figure 2b. According to LandGEM model, landfill area is going to accept solid wastes three more year than the actual closing year of the landfill. Therefore, the increased amount of total landfill gas has come from the difference between the model closure year (2031) and landfill real closing year (2028). It will be possible to produce landfill gas three more year to generate power which provides to contribution all power generation. When compared the two standards of LandGEM model which are CAA and AP-42, the total landfill gases were predicted much more (nearly twice) using by the CAA standard than AP-42 standard for the case of closure year calculation was NO.

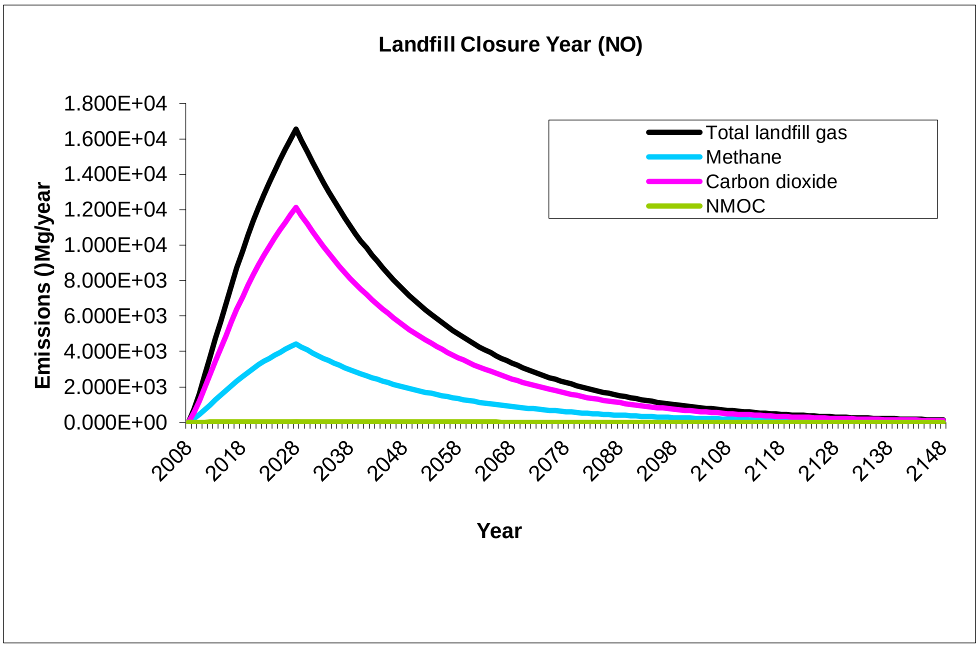

Figure 3a. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with AP-42 standards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area for the years between 2008 and 2020 (Mg/year, Model Closure Year=NO).

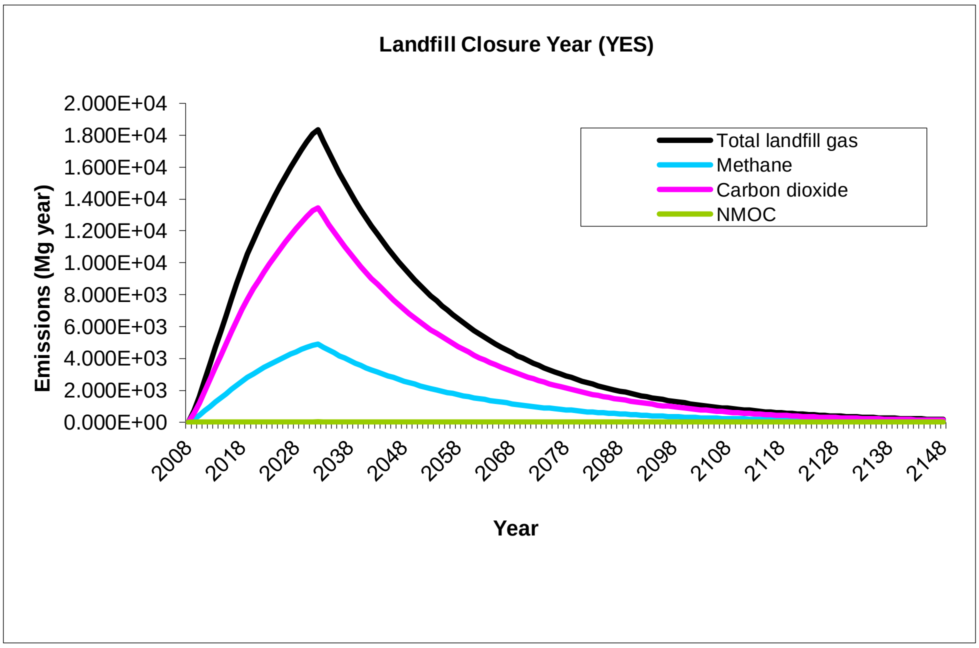

Figure 3b. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with AP-42 standards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area (Mg/yıl, Model Closure Year=YES).

Finally, *k* and *Lo* values were calculated manually according to the Equations of 2-5 and used in the LandGEM model as User Specified standard. Figure 4a and 4b also represent the amount of the total landfill gas, CH_4, CO_2 and NMOC values in annual megagrams (Mg/year) for both NO and YES situations obtained by the calculation with User Specified standards as the LandGEM model default in Erzurum Province Solid Waste Landfill area.

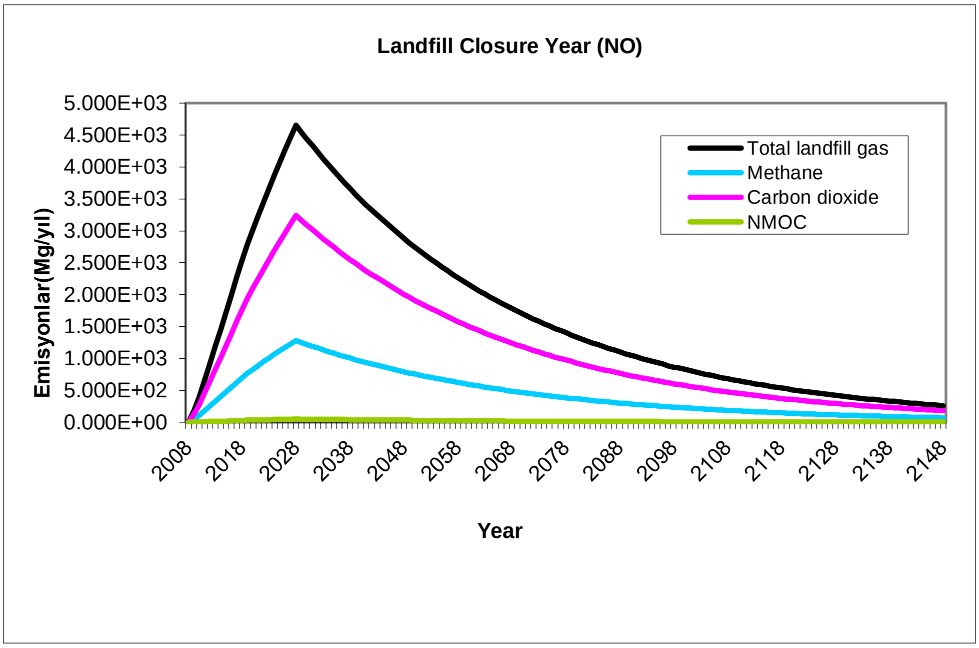

Figure 4a. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with User Speci-fied standards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area for the years between 2008 and 2020 (Mg/year, Model Closure Year=NO).

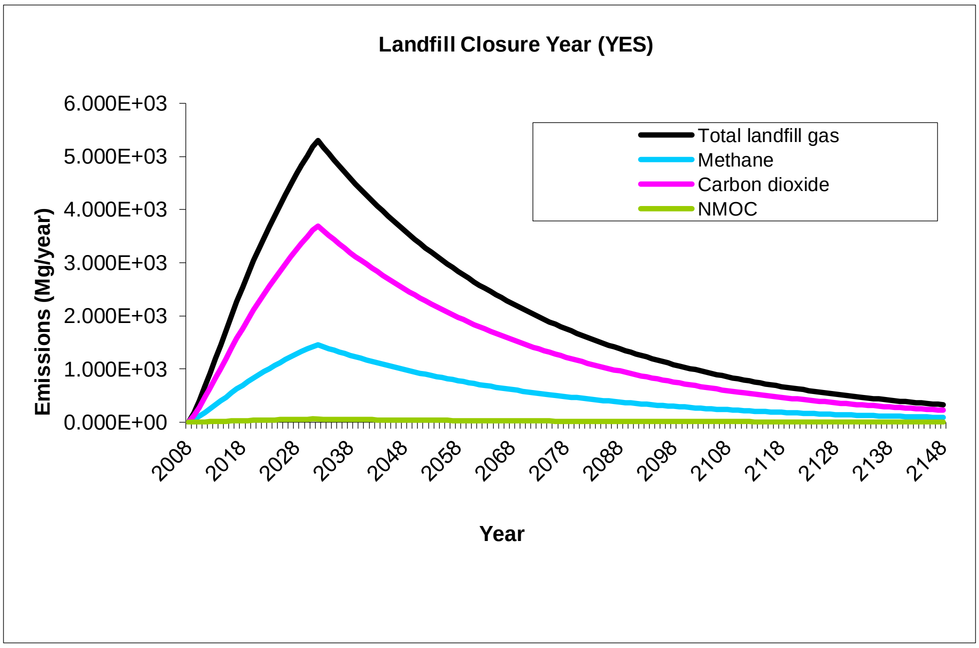

Figure 4b. The amount of the total landfill gas, CH_4, CO_2 and NMOC calculated with User Specified standards as LandGEM model default for Erzurum Municipality Solid Waste Landfill Area (Mg/year, Model Closure Year=YES).

In this case, total landfill gas and methane were predicted as 4.654x10^3 and 1.279x10^3 Mg/year (Figure 4a), respectively at the real closure year of the landfill area which is 2028. On the other hand, these gases were predicted as 5.186x10^3 and 1.452x10^3 Mg/year, respectively at the model closure year of 2031 in Figure 4b. When compared three standards, User Specified standard that is used manually calculated *k* and *Lo* have predicted less landfill gases than CAA and AP-42 standards. The range of the amount of total landfill gases for three standards was CAA, AP-42 and User Specified, respectively. The model closure year was calculated as 2031 for all three standards as well.

In the literature, *k* and *Lo* values ranged as 0.035-0.35 year^{-1} and 32.55-170 m^3/Mg, respectively, while they were specifically calculated as 0.024 year^{-1} and 42 m^3/Mg for Erzurum Municipality Landfill Area. On the other hand, EPA indicates that the appropriate values for *Lo* range from 56.6 to 198.2 (m^3/Mg) of waste. Except in dry climates where lack of moisture can limit methane generation, the value for the *Lo* depends almost completely on the type of waste present in the landfill that the dry organic content of the waste determines the *Lo* value. The higher the organic content of the waste, the higher the value of *Lo* (USEPA, 2011). It is thought that this difference is largely due to the differences in the organic content of the wastes and dry content in Erzurum. An accurate waste content and dryness analysis can be required for future modelling.

In the last part of the study, the landfill gases calculated with the LandGEM model were compared with the amount of CH_4 content measured in the field which started to be measured daily on-site since 2019 in the Erzurum Municipality Solid Waste Landfill Area. The monthly average values of methane gas measured from the landfill area was calculated as percentage and given in Table 3. For this comparison, the annual average CH_4 emissions for 2019, 2020 and 2021 were calculated as annually average because the LandGEM model has used the annual average. So as to the model default is not to calculate landfill closure year, the amount of methane calculated in the Figure 2a-3a-4a were used for the comparison of model and real measurement results.

Table 3. The field measurements of CH_4 content (%) of Erzurum Municipality Solid Waste Landfill Area.

	2019	2020	2021
January	53.06	52.13	59.29
February	52.11	52.80	59.87
March	52.71	53.70	65.12
April	53.03	52.26	58.52
May	52.17	51.56	60.38
June	50.38	54.79	60.91
July	52.10	57.38	55.31
August	51.48	58.55	59.09
September	51.57	59.95	55.04
October	51.62	56.46	50.43
November	51.43	57.66	51.37
December	56.53	58.44	48.24
Average	52.35	55.47	56.96

Although NMOC is not included in the landfill gases measured at the site, O_2 and H_2S measurements (<1%) are carried out at the landfill site. According to the results of on-site CH_4 measurements (Table 3), the CO_2 content of the total landfill gas can be easily predicted because the main part of landfill gases is CH_4 and CO_2. This phase is called as methanogenic stable phase in the literature that the highest CH_4 concentration is observed in. This phase is completed in an average of 10-20 years as the amount of total landfill gases gradually decreases. So, the model closure year of 2031 (with the lowest level) was verified with the methane content measurements in the field (Öztürk, 2018; Dai et al., 2021).

Additionally, it can be seen from Table 3 that the average value of CH_4 is calculated as 52.35%, 55.47% and 56.96%, while it is predicted as 57.22%, 56.62.02% and 55.77% in the LandGEM model with the User Specified standards, respectively which confirms that the in-situ measurements and User Specified standard validates each other. The total measured landfill gas in the area is obtained as 18.258.312 m^3, while the model estimates this amount as 19.606.347 m^3 for three year of 2019, 2020 and 2021. Finally, *k* and *Lo* calculated to Equations (2-5) for this study demonstrates that the User Specified calculation used in this study have shown the accuracy and proximity of the results when compared to the in-situ measurements. The NMOC values are measured below 1% for in-situ measurements and are neglected as model did.

The emissions obtained from the estimation of the landfill gas in Erzurum Solid Waste Landfill Area with the LandGEM model, were compared with the emissions ob-tained by applying the same model to different landfill in the literature and are shown in Table 4. Considering the amount of waste used in this study, it is seen that the estimated total landfill gases and CH_4 emissions are proportional and sensible that confirms the model estimation.

Table 4. The comparision of literature emissi ons results estimated from different landfills by LandGEM

Landfill	Project Waste Amount, ton/year	Model Year	Landfill gas, m^3/year	CH_4, m^3/year
Kakia, Mekke (Osra et al. 2021)	3100	2003-2143	190.5×10^7	95.2×10^7
Sivas, Turkey (Yıldırım, 2020)	350	2014-2154	20.7×10^7	10.6×10^7
Samsun, Turkey (Atmaca, 2015)	500	2008-2207	249.3×10^7 (CAA)	124.6×10^7 (CAA)
Erzurum, Turkey (This study)	120	2008-2148	2.592×10^7 (CAA)	1.296×10^7 (CAA)

By means of the results obtained, the formation of CH_4 gas per unit waste amount was calculated separately for all three parameters of CAA, AP-42 and User Specified and was found in the range of 8.83-68.12 m^3/Mg. Biodegradability calculations have shown that the generation of CH_4 gas per unit ton of waste is in between 6-230 m^3/ton (m^3/Mg) in the literature studies. Therefore, it has been seen that the formation of CH_4 gas per unit waste obtained in this study is in accordance with the literature calculations (Bilgili, 2002). Hosseini et al. (2018) calculated the CH_4 production capacity of the Iranian city of Hamedan solid waste landfill as 107 m^3/Mg (Hosseini et al., 2018).

Conclusions

In this study, LandGEM model was used for determining landfill gas generation for three different standard values of inventory (CAA, AP-42, User Specified) in Erzurum Municipality Landfill Area. According to the results of the gas generation amounts by using model's standards, it is seen that lower methane gas amounts are obtained by User Specified values of *k* and *Lo* calculated for the area. According to the results of the gas generation amounts by using models, it is seen that lower methane gas amounts are collected compared to potential due to the operating conditions. All three standards predict that the landfill closure year is going to be 2031 which is three more years than landfill project year of 2028. Since there is already electrical energy production from the Erzurum Municipality Landfill Area, it will be possible to generate increased landfill gases as well to power generation. In the literature, *k* and *Lo* values ranged as 0.035-0.35 $year^{-1}$ and 32.55-170 m^3/Mg, respectively, while they were specifically calculated as 0.024 $year^{-1}$ and 42 m^3/Mg for Erzurum Municipality Landfill Area. The *Lo* value of the area calculated and used in LandGEM as User Specified was found within the range given in literature studies. The *k* value is generally lower in the literature studies which implies the dry landfill sites. The LandGEM model can be used successfully in similar areas of which waste content and meteorological conditions that don't have a biogas facility. The model provides a good analysis in terms of economic and energy analysis via its emission estimation before settling a biogas unit.

Compliance with Ethical Standards

Conflict of interest

The authors declared that for this research article, they have no actual, potential or perceived conflict of interest.

Author contribution

The contribution of the authors to the present study is equal.

All the authors read and approved the final manuscript. All the authors verify that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Ethics committee approval is not required.

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Data availability

Not applicable.

Consent for publication

Not applicable.

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