JOURNAL OF THE CIVIL ENGINEERING FORUM

Journal of the Civil Engineering Forum, September 2021, 7(3): 239-252
DOI 10.22146/jcef.62824
Available Online at http: https://jurnal.ugm.ac.id/jcef/issue/archive

Methane Emission Estimation and Dispersion Modeling for a Landfill in West Java, Indonesia

Soni Pratamayudha Wijaya, Siti Ainun, Didin Agustian Permadi**
Department of Environmental Engineering, Institut Teknologi Nasional (ITENAS) Bandung, INDONESIA
JL. PHH Mustafa 23 Bandung 40123, West Java
*Corresponding authors: didin@itenas.ac.id

SUBMITTED 4 January 2021 **REVISED** 7 March 2021 **ACCEPTED** 23 March 2021

ABSTRACT Methane gas (CH_4) is a greenhouse gas that can potentially induce global warming and it is known as surface ozone precursor. CH_4 is generally produced from biological process occurred at the landfill which is not equipped with CH_4 recovery and treatment system. Note that, very few of landfills in Indonesia have been operated as sanitary landfill but rather most of them act as dumping site. One landfill in West Java Province is Sarimukti Landfill which receives nearly 604,674 ton of solid waste annually. Existing studies have been using the first tier of the Intergovernmental Panel on Climate Change (IPCC) guideline for the emission estimation which provides high uncertainty due to the international default data. In addition, there are uncertainties for the multi years estimation because the kinetic rate of biological processes was not involved in the calculation. To fill in this gap, this research was conducted to use an alternative of methodology for estimating CH_4 from landfill using a well known software of the Landfill Gas Emissions Model (LandGEM) which facilitates biological reaction in the calculation. We will also perform calculations using the traditional IPCC method for the Sarimukti landfill as a case study. To quantify the impact of CH_4 emission, its dispersion was calculated using the AMS/EPA Regulatory Model (AERMOD). Potential impact on surface ozone formation was assessed using ozone formation potential (OFP) metric. The results of this study indicate that methane gas emissions have increased every year, where the highest emissions occurred in 2025 of 14,810.41 Mg/year (LandGEM) and 11,462.66 Mg/year (IPCC). Likewise, the potential for OFP from methane gas concentrations has increased every year where the highest concentration of surface ozone formation is in 2025 of 183,40 Mg/year. Meanwhile, the methane emission (CH_4) has a dispersion pattern which is influenced by meteorological factors around the Sarimukti landfill.

KEYWORDS Methane; LandGEM; IPCC; Ozone ; AERMOD.

1 INTRODUCTION

Waste management that is dominantly implemented in Indonesia covers the collection, transport and disposal method, which in turn it will be disposed to a landfill (Artiningrum, 2018). Landfill will accept all the risks that arose from the waste processing pattern, especially the risks associated with leachate pollution into groundwater or water bodies, air pollution by gases, and the greenhouse effect and the number of disease vectors (Rahmi, Sasmita *et al.*, 2017). In addition, the decomposition process can result in the formation of greenhouse gas of methane (CH_4), which is known to cause negative impacts such as global warming and secondary ozone formation (Kamelia, 2015). The waste delivered into the landfill contains huge portion of, organic materials which will undergo anaerobic degradation process which can be a driving factor for global warming (Chiemchaisri, *et al.*, 2007). Moreover, the largest gas emitted from landfill activities is methane gas (Kurniasari, *et al.*, 2014), this gas has a destructive potential that is 20-30 times greater than carbon dioxide (CO_2) which is produced by landfill piles. The higher waste piles without further processing, causes greater methane gas emissions (Septiani, 2019). When released into the atmosphere, methane gas emissions reacts with primary air pollutants such as nitrogen oxides (NO_x) and carbon monoxide (CO). The products of these reactions then forms secondary air pollutants ozone (O_3), which is toxic to humans and plants (Permadi and Oanh, 2008). Furthermore, Sarimukti landfill is located in Cipatat District, West Bandung Regency, Indonesia. Under the present waste management condition, the attempted mode of operation is a controlled landfill method. The use of this method is to improve existing waste management, in order to achieve better results. Annually, the amount of solid waste delivered to the landfill is known to be 604,674 ton/year

(Purnamasari, 2019). Also, waste generation is found to be influenced by several factors, including weather, frequency of collection, season, socio-economic level, and per capita income (Damanhuri and Padmi, 2010).

This method is also used to reduce the pollution, which utilizes several facilities in the landfill system. One of these gas management facilities is reportedly built by planting ventilation pipes in the garbage heap. These pipe are useful for channeling the gas formed into the air to avoid emission build-up in the wastes, which are found to often cause an explosion. However, this facility is built without prior use of methane utilization facilities. Due to this case, methane is directly channeled into the air without further management, which potentially forms a secondary pollutant, namely ozone (O_3). This surface formation of ozone (O_3), poses greater risks to the environment, due to its level of toxicity.

This study aims to determine the amount of methane gas emissions formed and distributed, when released into the atmosphere. Additionally, it also aims to calculate the potential surface ozone formation, due to the reaction of methane gas with natural air emissions, which leads to the production of toxic secondary pollutants in the environment. Moreover, the results obtained should be used as evaluation materials for the Sarimukti landfill manager, in order to have the ability to reduce air pollution, via the utilization of methane gas.

On a regular basis, Indonesia are known to have reported their greenhouse gas emission (i.e., CH_4) to the United Nations Framework Convention on Climate Change (UNFCCC). One of the important source of CH_4 emission is obtained from landfill activity, with previous studies using the first tier of the Intergovernmental Panel on Climate Change (IPCC) guideline for the calculation (Sari, 2018). This estimation provides high uncertainty, due to the usage of international default data, non-involvement of biological processes' kinetic rate, and the zero assumption of emission after landfill closure. Therefore, an alternative methodology is being conducted, by using a software known as the Landfill Gas Emissions Model (LandGEM). This model helps in facilitating biological reaction in the calculation, as the results are also being compared to the traditional IPCC method. In order to quantify the impact of CH_4 emission, its dispersion was also calculated using Aermic Model (AERMOD). Also, potential impact on surface ozone formation was assessed by using OFP (Ozone Formation Potential) metric. Therefore, this framework demonstrates an integrated approach for emission to impact relation, due to the landfill operation in Indonesia, which is also replicated in other landfills.

2 METHODS

2.1 Initial observations

This research was conducted on methane gas only, as other gases formed from degradation of organic waste were not conducted. The selection of methane gas as a measured parameter was due to its reaction with natural gases, such as NO_2 and CO, which in turn results in the formation of secondary surface pollutants, namely ozone. Therefore, this research was conducted to determine the methane gas emissions that were formed and distributed from the operational activities of Sarimukti Landfill.

2.2 Data collection

Secondary data were mostly used in this study. These data were obtained through existing conditions, as well as literature studies published by various related agencies. These required secondary data are presented in Table 1.

Table 1. Secondary Data

No	Data Required	How to Get Data	Uses of Data
1	Waste Generation	Study of literature from journals and previous research	This is to determine the amount of waste generation entering the Sarimukti landfill
2	Total population	Study of literature from data released by BPS Bandung City	To determine the amount of waste generation, and methane gas emissions, via population projections
3	Meteorology	Study of literature from data issued by Bandung City Air Station (Husein Sastranegara)	To determine the rainfall, temperature, wind speed & direction, as well as humidity data, which were to be used for modeling with AERMOD

2.3 Methane Emissions Inventory

This inventory was conducted, in order to determine the emissions released from the Sarimukti landfill operational activities, via the use of the LandGEM software. The results of this model were likely to be in the form of long-term methane emission estimates. After this model data were obtained, they were compared with the results of calculations, via the use of the IPCC Guideline 2006 method. Moreover, this comparison process was accompanied by modeling the distribution of methane gas. Mathematically, LandGEM had the following equation (USEPA, 2005),

$$Q = Lo.R.(e^{-kc} - e^{-kt}) \tag{1}$$

where Q is the volume of methane produced (m^3/year), Lo is the potential for methane gas formation from waste (m^3/ton), R is the rate of waste received at landfill each year (tonnes/year), k is the degradation constant of orde 1 (per year), c is the amount of time until the landfill closes (year), t is the time from the time of operation to the present (year), and e is the konstanta euler.

In putting the required data parameter (such as data on waste generation), was the first step in operating the LandGEM model. Afterwards, conducting a review process to check the inputted data was carried out. Moreover, a worksheet containing the calculation for methane was provided, as the results for several gases, such as the total landfill emission, CH_4, carbon dioxide, and NMOC, were also obtained. Conclusively, these results were represented in graphical form. However, the IPCC Guideline 2006 method had the following equation (Sari, 2018),

$$CH_4T\ Generation = DDOCdecompT \times f \times 1612 (2)$$

Where $CH_4T\ Generation$ is the amount of CH_4 generated from decomposed material, $DDOCm\ decompt\ T$ is $DDOCm$ decomposed in year T (Gg), f is the fraction of methane (CH_4) in the generation of gas in landfill (fraction), and 16/12 is the CH_4/C molecular weight ratio (ratio)

In the IPCC method, the first step was to input the parameters to be searched, such as the Methane Correction Factor (MCF), Activity, and Amount Deposit data. Finally the Results (MSW) worksheet was provided, in order to display the outcomes of calculating methane gas emissions.

2.4 Methane Emissions

Sarimukti is one of the sanitary landfill located in West Java province. This location is known for its risk of methane gas formation, as a result of organic matter degradation. Also, it was reported that Sarimukti landfill had not carried out further management, which were related to the generation of the methane gas. Presently, it is limited to channeling the gas through a pipe planted in the garbage pile, with emission directly passed into the atmosphere.

The landfill itself is regional to the West Java region, which receives waste from Bandung City & Regency, as well as West Bandung and Cimahi Cities. Therefore, the highest annual amount of solid waste that arrived at the landfill was 667 Gg/year, as indicated in Table 2 (Purnamasari, 2019).

Table 2. Waste Generation

Year	Waste Generation (Tons / Day)	Waste Generation (Tons / Year)
2015	1,601	584,365
2016	1,649	601,885
2017	1,603.2	585,168
2018	1,600	584,000
2019	1,830	667,950

Source: PD Kebersihan Bandung City, 2019

Afterwards, the waste generated were transported to the Sarimukti landfill for further management. Besides the use of this data, the waste generation entering the Sarimukti landfill was closely related to the population. A large population growth was observed to indirectly increase the amount of waste generation. Moreover, the population data was processed using the 2006 IPCC Guideline model, in order to estimate the generation of waste, as well as the formation of methane gas. Based on Tasrin (2014), the city of Bandung had a service level percentage of 66-72%, which was greater than that of Cimahi (16.4%), as well as Bandung and West Bandung Regencies (10.76% & 7.8%), respectively. However, in this study, the population data was only used in Bandung City, as presented in Table 3 (Statistik, 2015-2019).

Table 3. Total Population

Year	Total Population (Person)
2015	2,441,551
2016	2,450,995
2017	2,460,475
2018	2,469,993
2019	2,479,547

Source: BPS Bandung City, 2015-2019

Furthermore, the data was processed using the LandGEM and IPCC Guideline 2006 methods, in order to estimate methane gas emissions. The use of these methods was due to their assistance in modeling methane gas (CH_4) emissions, which substituted and complemented to the lack of data required. Therefore, both methods had provided numbers/values, which were used as a substitute for the lack of data required, in this study.

Based on the use of the LandGEM method, the results were observed to provide information about the long-term consequences of methane gas, due to the ability of the model to simulate CH_4 emission modeling for the next 80 years. This was also used as an evaluation material in the management and utilization of methane gas, in order to reduce the formation of methane gas emissions. Meanwhile, the IPCC Guideline 2006 method was used in this modeling because of its default values, which that had been adjusted to the humid and wet tropical climate conditions.

2.5 Dispersion model of AERMOD

The inventory data used LandGEM and IPCC 2006 models, as well as obtain the calculation for the potential of surface ozone formation. A simulation of methane gas distribution was also carried out by using the AERMOD (American Meteorology Society Environmental Protection Agency Regulatory Model) software, in order to assist the distribution model simulation process. The result obtained was a map of methane gas concentration distribution, which was observed around the Sarimukti landfill site.

In processing the dispersion model with AERMOD, meteorological data, such as cloud cover, air temperature & pressure, wind direction & speed, ceiling height, rainfall, and solar radiation, was also needed. However, the meteorological parameter used in this study was hourly data, which was obtained from the period of January to December 2019. These data were further obtained from the nearest airport station, which was closest to the study location. These meteorological data obtained was processed via the use of the Microsoft Excel program, where they were compiled into one worksheet, which was to be monitored and predicted by the AERMET system. After the compilation of the data into the worksheet, the next step was to convert the excel outcome into a SAM file format, via the use of the AERMET program. After processing the data, the output was obtained in the .SFC and .PFC file formats, where both were used to run AERMOD (Ancilla, 2014). Additionally, the meteorological processing with AERMET is known to be a series of processes, which are used for running AERMOD devices.

2.6 Ozone forming potential

After the inventory data had been obtained, calculations were carried out, in order to determine the potential of surface ozone formation from the methane gas concentration. Based on this information, the potential of surface ozone formation assessment was carried out using the following equation (Olumayede, 2014),

$$Potential\ Ozone\ Generation = Concentration\ (i) \times MIR\ Coefficient\ (i) \quad (3)$$

Where $Ozone\ Generation\ Potential$ is the potential amount of ozone generated, $Concentration\ (i)$ is the concentration of gas formed (gram/second), and $MIR\ (Maximum\ Incremental\ Reactivity)\ coefficient$ is the coefficient of increasing the maximum reactivity coefficient.

The Maximum Incremental Reactivity data were obtained from the scientific journal on the Ozone-Forming Potential of Reformulated Gasoline. Additionally, the OFP results dealt with some uncertainties, such as the local meteorological condition, CH_4 reactivity, and the other unknown photochemical smog precursor concentrations (NO and VOC).

3 RESULTS

3.1 Methane Emissions IPCC Method Guideline 2006

The default approach model used was the IPCC Guideline 2006 method, which involved the equation that connects data on waste generation, degraded organic matter content, landfill conditions, and the amount of methane produced. The data used in this model was the number of residents in the city of Bandung. Also, the population data was processed in the IPCC Guideline 2006 method, in order to obtain the values of waste generation. This values were then processed by using the LandGEM method. Based on population data, the results of waste generation were presented in Table 4.

Tabel 4. Waste Generation Data Based on Population Results of the IPCC Guideline 2006 Processing Method

Year	Waste generation resulted from processing the IPCC Guideline 2006 method	
	Gg/year	Mg/year
2015	388.94	388939.07
2016	390.44	390443.50
2017	391.95	391953.67
2018	393.47	393469.88
2019	394.99	394991.84

Source: IPCC Guideline 2006, 2020

Table 4. showed the results of waste generation, which had been processed using the IPCC Guideline 2006 method. These were generated from the default values of waste per capita, which were provided by the IPCC system. Conversion to Megagram/year was also required, in order to be used in the LandGEM method. After the waste generation data had been obtained, the estimation of methane gas (CH_4) emissions was further calculated via the IPCC Guideline 2006 method, as indicated in Table 5.

Table 5 also showed series of stages from the 2006 IPCC Guideline method, in order to obtain the value of methane gas (CH_4). The methane gas emissions were produced by the IPCC method, by using the amount of waste generation that had already been processed. These generated wastes by means of default from the landfill, were monitored and predicted at a value of about 59% (this figure is the default value of the IPCC Guideline 2006 method). Therefore, the following is a graphical representation of the estimated methane gas emissions from the landfill, using the IPCC Guideline 2006 method.

Based on Figure 1, it was observed that methane gas emissions increased yearly, due to the increment of waste entering the landfill each year. The largest methane gas was observed in 2025, at about 11,46266 Gg or 11,462.66 Mg, where the Sarimukti landfill experienced a closure.

Table 5. Estimation of Methane Emissions by IPCC Guideline 2006 Method

Year	Waste Generation	MCF	DOC	$DDOC_m$	$DDOC_m$ not reacted	$DDOC$ maT	$DDOC_m$ accumulated	$DDOC_m$ aT DecompT	CH_4 generated	CH_4 generated
	Gg	fraction	fraction	Gg	Gg	Gg	Gg	Gg	Gg	Mg
2015	388.94	1.00	0.17	33.06	33.06	0	63.92	2.07	1.38	1382
2016	390.44	1.00	0.17	33.19	33.19	0	93.08	4.02	2.68	2681.74
2017	391.95	1.00	0.17	33.32	33.32	0	120.54	5.86	3.91	3905.37
2018	393.47	1.00	0.17	33.44	33.44	0	146.40	7.59	5.06	5057.37
2019	394.99	1.00	0.17	33.57	33.57	0	170.76	9.21	6.14	6142.28
2020	396.52	1.00	0.17	33.70	33.70	0	193.72	10.75	7.16	7164.34
2021	398.05	1.00	0.17	33.83	33.83	0	215.36	12.19	8.13	8127.53
2022	399.59	1.00	0.17	33.97	33.97	0	235.78	13.55	9.04	9035.57
2023	401.14	1.00	0.17	34.10	34.10	0	255.03	14.84	9.89	9891.96
2024	402.69	1.00	0.17	34.23	34.23	0	273.21	16.05	10.70	10699.97
2025	404.25	1.00	0.17	34.36	34.36	0	290.38	17.19	11.46	11462.66

Source: IPCC Guideline 2006, 2020

Where MCF is the methane correction factor, DOC is the degradable organic carbon, $DDOC_m$ is the mass of $DDOC$ deposited year, and $DDOC_{m\ not\ reacted}$ is the mass of $DDOC$ deposited in inventory year T, remaining not decomposed at the end of year. In Table 5, $DDOC_{maT}$ is the mass of $DDOC$ deposited in inventory year decomposed during the year, $DDOC_{m\ accumulated}$ is total mass of $DDOC$ left not decomposed at end of year, and $DDOC_{maT\ DecompT}$ is total mass of DDOC decomposed in year.

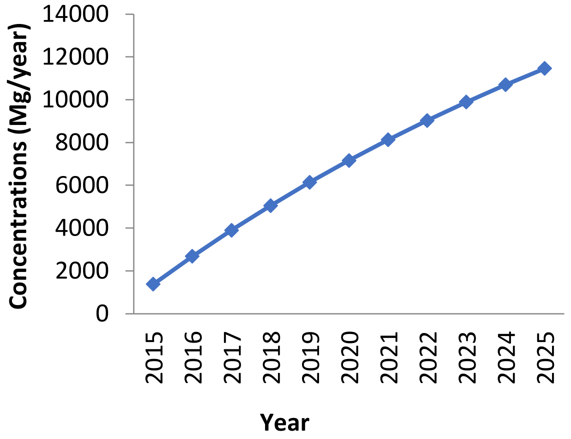


Figure 1. Methane Emissions by IPCC Guideline 2006 Method
(Source: IPCC Guideline, 2020)

3.2 Methane Emissions by LandGEM Method

The waste generation entering the Sarimukti landfill, which was processed in the LandGEM method, used more or less data for the last 5 years. This was indicated in the waste generated in 2015-2019, where a relative increase was observed, via the data obtained from PD Kebersihan, Bandung City. These data were further used to project the waste generation entering the Sarimukti Landfill till 2025, in terms of determining the amount of methane emission generated. Also, these data and the methane gas emission formed were compared to the waste generation parameters, which were shown in Table 4.

The largest methane gas emissions formed by those two methods were further selected, in order to give an illustration of the existing conditions of methane gas emissions, in the Sarimukti landfill. Based on data from PD Kebersihan, the results of the LandGEM method in estimating the amount of waste entering the Sarimukti landfill, were presented in Table 6.

Based on the data from PD Kebersihan, Table 6 showed the amount and projections of waste generation entering the Sarimukti landfill, during the periods of 2015-2025, in Bandung City. Also, the amount of waste entering the landfill as at 2015 was estimated at 584.365 Mg/year, and was observed to have increased to 667.950 Mg/year in 2019. After the estimation that had entered the landfill, the LandGEM method then estimated the methane gas emissions, which were obtained from the waste generation. The results were further presented in Table 7.

Table 7 showed that in 2015, the methane gas produced was 1,052.40 Mg/year, which then continued to increase until 2025, at 14,810.41 Mg/year. This increase was due to the large amount of organic waste, which had been degraded by microorganisms, in order to produce methane gas. A graphical representation of this process is presented in Figure 2.

Table 6. Amount of Waste Generation Entering Sarimukti landfill Based on Data from PD Kebersihan

Year	Waste Accepted		Waste-In-Place	
	(Mg/year)	(short tons/year)	(Mg)	(short tons)
2015	584365	642801.5	401500	441650.00
2016	601885	662073.5	985865	1084451.50
2017	585168	643684.8	1587750	1746525.00
2018	584000	642400.0	2172918	2390209.80
2019	667950	734745.0	2756918	3032609.80
2020	667950	734745.0	3424868	3767354.80
2021	667950	734745.0	4092818	4502099.80
2022	667950	734745.0	4760768	5236844.80
2023	667950	734745.0	5428718	5971589.80
2024	667950	734745.0	6096668	6706334.80
2025	0	0.0	6764618	7441079.80

Source: LandGEM, 2020

Table 7. Estimation of Methane Emissions Based on Data of Waste Generation Entering Sarimukti landfill

Year	Methane		
	(Mg/year)	(m^3/year)	(av ft^3/min)
2015	1052.40	1577454.73	105.99
2016	2542.85	3811515.49	256.10
2017	4020.78	6026811.87	404.94
2018	5396.94	8089565.75	543.54
2019	6716.08	10066848.94	676.39
2020	8203.55	12296433.19	826.20
2021	9632.68	14438594.19	970.13
2022	11005.79	16496759.86	1108.42
2023	12325.05	18474223.70	1241.28
2024	13592.58	20374150.07	1368.94
2025	14810.41	22199579.26	1491.59

(Source: LandGEM)

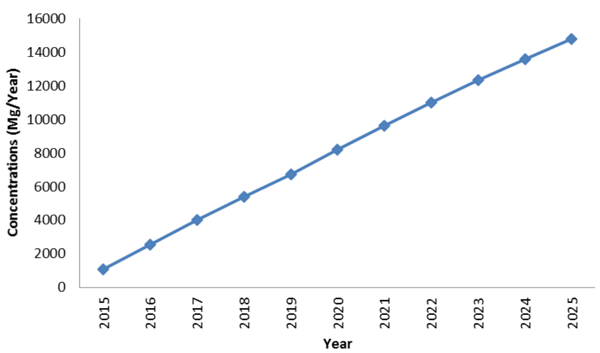


Figure 2. Graph of Methane Gas Formation Based on Waste Generation Data Entering Sarimukti landfill
(Source : LandGEM, 2020)

Based on data from PD Kebersihan, the graph shown in Figure 2 illustrated the methane gas emissions produced by the Sarimukti landfill during the last 5 years, until its closure in 2025. Based on the results of the LandGEM model on these data, it was stated that the methane gas production, which occurred in the Sarimukti landfill, continued to increase until its closure. This is likely to continue because, as long as the landfill is not closed, the occurrence of waste generation also remains continuous, in order to influence the production of methane gas at Sarimukti.

In addition to processing the data released by PD Kebersihan in this LandGEM method, the process of information was also carried out via the waste generation parameters obtained from the IPCC Guideline 2006 method. Based on the IPCC waste generation parameters, the results of the LandGEM method in estimating the amount of garbage entering the Sarimukti landfill are indicated in Table 8.

Based on the data from IPCC processing, Table 8 showed the amount and projections of waste generation entering the Sarimukti landfill, during 2015-2025. The amount of waste that entered the landfill was estimated at 388,939.07 Mg/year in 2015, which further increased to 394,991.84 Mg/year in 2019. Moreover, the LandGEM method estimated the methane gas emissions, which was generated from this waste. Based on the estimation of the resulting methane gas emissions, the results were presented in Table 9.

Table 8. Amount of Waste Generation Based on Data that has been Pre-processed Using the IPCC Method

Year	Waste Accepted		Waste-In-Place	
	(Mg/year)	(short tons/year)	(Mg)	(short tons)
2015	388939.07	427832.98	387437.19	426180.91
2016	390443.50	429487.85	776376.27	854013.90
2017	391953.67	431149.03	1166819.77	1283501.75
2018	393469.88	432816.87	1558773.44	1714650.78
2019	394991.84	434491.02	1952243.32	2147467.66
2020	394991.84	434491.02	2347235.16	2581958.68
2021	394991.84	434491.02	2742227.00	3016449.70
2022	394991.84	434491.02	3137218.84	3450940.72
2023	394991.84	434491.02	3532210.67	3885431.74
2024	394991.84	434491.02	3927202.51	4319922.76
2025	0.00	0.00	4322194.35	4754413.78

Source: LandGEM, 2020

Table 9. Estimation of Methane Gas Emissions Based on Pre-processed Data Using the IPCC Method

Year	Methane		
	(Mg/year)	(m^3/year)	(av ft^3/min)
2015	1015.54	1522203.32	102.28
2016	1995.19	2990620.93	200.94
2017	2940.37	4407371.83	296.13
2018	3852.45	5774504.41	387.99
2019	4732.74	7093988.03	476.64
2020	5582.51	8367713.57	562.23
2021	6398.95	9591495.61	644.45
2022	7183.38	10767292.47	723.45
2023	7937.05	11896985.67	799.36
2024	8661.18	12982382.97	872.28
2025	9356.90	14025221.24	942.35

Source: LandGEM

Table 9 showed that methane gas produced in 2015 was 1,015.54 Mg/year, and continued to increase until 2025, at a value of 9356.90 Mg/year. The graphical representation of this result is also presented in Figure 3.

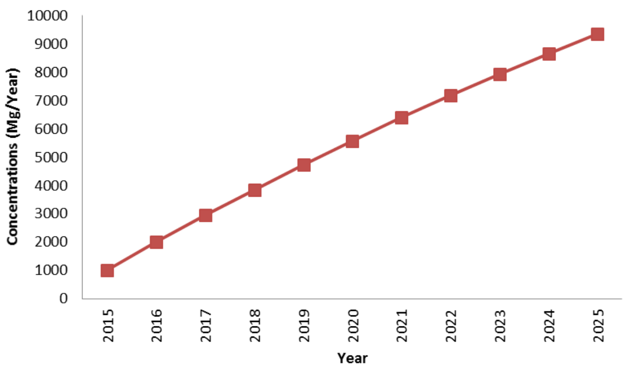


Figure 3. Graph of Methane Gas Formation Based on Pre-Processed Data Using the IPCC Method
(Source : LandGEM, 2020)

The graph shown in Figure 3 illustrated the produced methane gas emissions, based on the waste generation data from the IPCC. Similar to the data generated from PD Kebersihan, it was stated that the methane gas production that occurred at Sarimukti landfill, continued to increase until its closure. The results of the methane gas emissions using these two data were further compared, in order to determine the largest emission value generated. Based on the waste generation data used, the graphical representation of the methane gas emission comparison is illustrated in Figure 4.

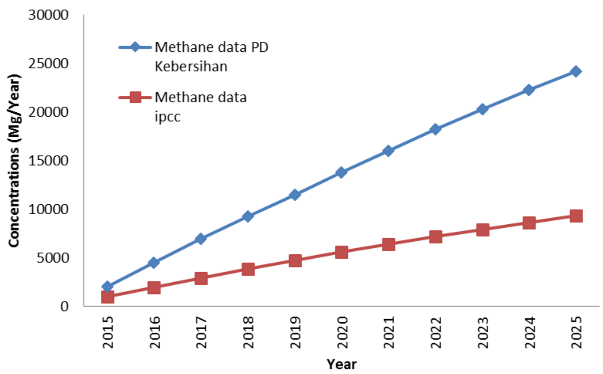


Figure 4. Comparison Graph of LandGEM Method Methane Emissions
(Source : LandGEM, 2020)

Furthermore, Figure 4 showed the comparison of methane gas emissions, which was obtained based on the waste generation data used. In the graphical representation, it was also observed that methane gas entering the Sarimukti landfill (LandGEM method) was greater than the emission generated by the IPCC method. These differences were caused by the generation data that were inputted into the LandGEM method.

Based on the two methane gas production, the largest emission data was selected for further processing, through the use of the AERMOD. The selected emission data used information from PD Kebersihan, due to its similarity to existing waste generation entering the Sarimukti landfill, as well as the conditions of the study location. Generally, it was stated that the concentration of methane gas emissions, based on the two methods, showed different results, where the estimation outcomes via the use of the LandGEM model were greater, compared to those of the IPCC. This was reportedly stated to occur, due to differences in the similarities and types of input parameters used.

3.3 Comparison of the two methods

Methane emission estimation using the two methods (LandGEM and 2006 IPCC Guideline method), were certainly observed to produce different emissions. This differences occurred due to the possession and usage of different default systems, in order to influence the results of methane gas emissions produced. Based on the comparisons of the two methods, the results were graphically presented in Figure 5.

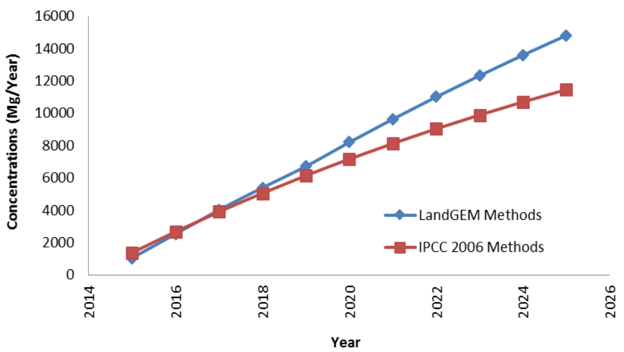


Figure 5. Comparison of Methane Emissions from the IPCC Guideline 2006 and LandGEM Methods
(Source: IPCC Guideline dan LandGEM, 2020)

According to Figure 5, it was observed that the yearly estimation of methane gas emissions had increased, where the highest value occurred in 2025, at 14,810.41 Mg/year (LandGEM) and 11,462.66 Mg/year (IPCC), respectively. The results of this study are much greater than that of Artiningrum, T. (2018), which stated that the methane gas emissions produced from waste generation was 2730.26 Mg/year in 2025. This was likely to occur, due to the differences in coverage and specificity of the data used, as well as the accuracy level of the results. However, there were differences between the two methods, as the LandGEM model was observed to be greater than the 2006 IPCC Guideline, based on the graphical representation. This occurred due to the LandGEM method using a formula of orde two. Besides that, the LandGEM method calculated on waste age, as well as nutrients available to the microorganisms.

3.4 Dispersion of Methane (CH_4) Emissions

The formation of methane gas emissions from the waste generation entering the Sarimukti landfill was unable to be separated from the degradation process of organic matter, which was contained in the garbage. Sarimukti landfill, which only managed the gases channelled through pipes, caused the methane emissions to be released directly into the atmosphere, without any treatment. Based on this, it was necessary to create a method, in order to determine the dispersion level of the emission, when released into the air. It was also necessary to know the toxicity level of the methane gas dispersed into the atmosphere, in order to determine a suitable method, which is likely to be used as an evaluation material, in minimizing the emission released into the surrounding environment, especially the air around the Sarimukti landfill.

The dispersion of methane gas emissions was also influenced by meteorological factors in the Sarimukti landfill area, such as air temperature, humidity, and pressure, wind direction & speed, as well as rainfall. This data should always be obtained from the nearest meteorological location to the study area, which in this case was the Husein Sastranegara Bandung station. Furthermore, the dispersion of methane gas emissions was processed, via the use of the AERMOD simulation model (The American Meteorology Society Environmental Protection Agency Regulatory Model). Methane emissions that have been calculated were mapped, in order to determine its amount at the Sarimukti landfill. The purpose of this mapping was to determine the amount of methane gas emissions formed from each area in the Sarimukti landfill, before simulating the distribution through the use of AERMOD. The results were further presented in Figure 6.

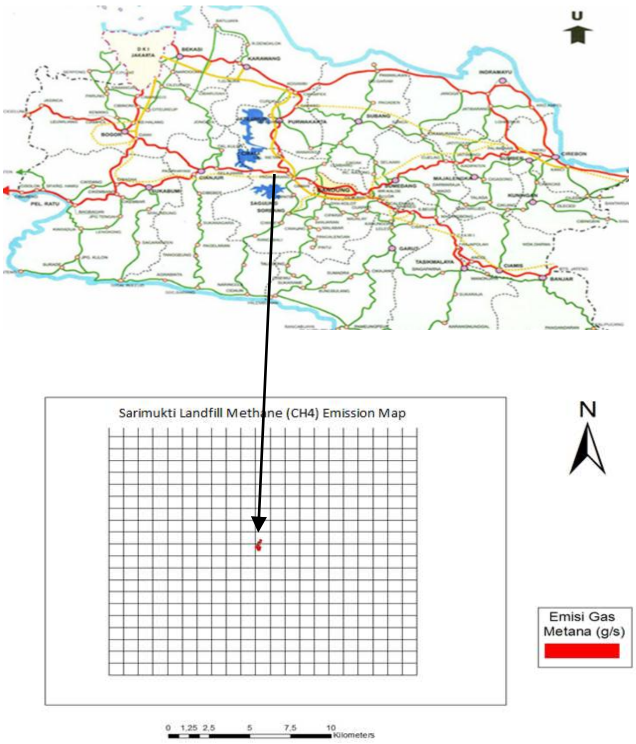


Figure 6. Methane Emission Map

3.4.1 Wind Direction and Speed

Generally, wind direction and speed were known from the data released by the Meteorology, Climatology and Geophysics Agency (BMKG). Based on meteorological data from the Husein Sastranegara Bandung station within the period of January to December 2019, the Wind Rose result was obtained and represented in Figure 7.

From the graph in Figure 7, it was observed that the highest wind speed was ⩾ 11.10 m/s, with the lowest at 0.50–2.10 m/s. Based on these data, the wind speed in Sarimukti landfill had the highest occurrence frequency, at speeds below 0.50 m/s (59.46%). From this graph, it was also observed that the dominant wind direction throughout 2019 was heading to the east.

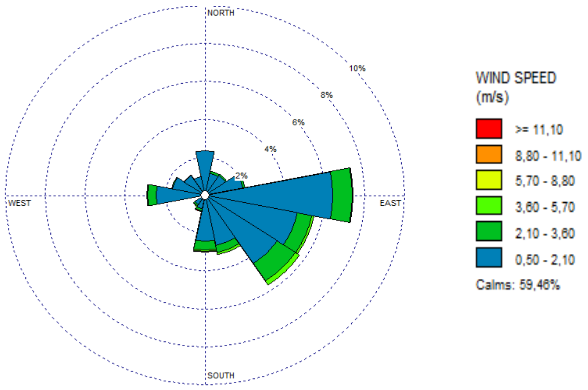


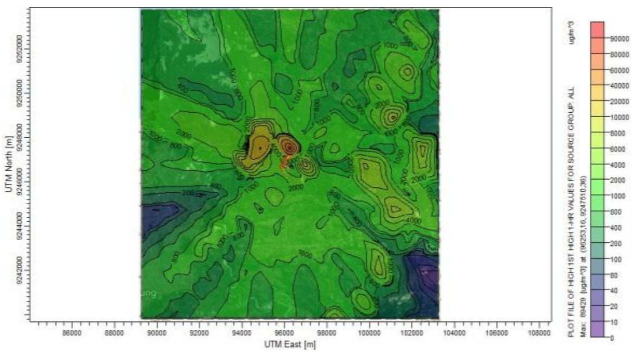
Figure 7. Regional Wind Rose Chart of 2019

3.4.2 Dispersion of Methane Emissions from the IPCC Guideline 2006 Method Data

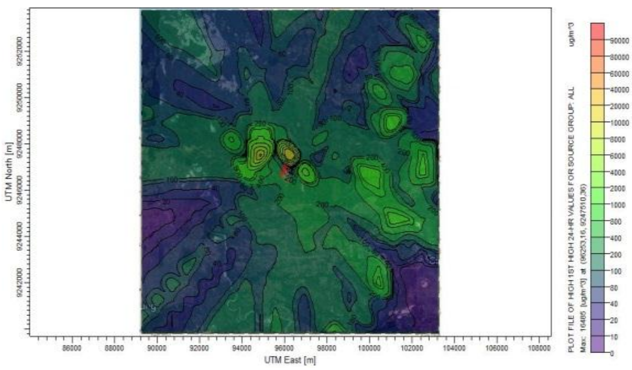
The methane gas emissions used in this study were of the highest data, which had been processed via the use of the IPCC Guideline 2006 method. These data were also converted from Mg/year to g/second units, in order for them to be read by the system of AERMOD View software. Also, the highest methane emission in this method was observed in 2025.

The following were the estimation result of methane gas distribution, via the use of the IPCC Guideline 2006 method. The results obtained for a period of 1 & 24 hours, as well as 1 year, were observed in Figure 8 (a), (b), and (c), with the maximum methane gas distribution values at 89,429 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), 16,485 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), and 1,729 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), respectively.

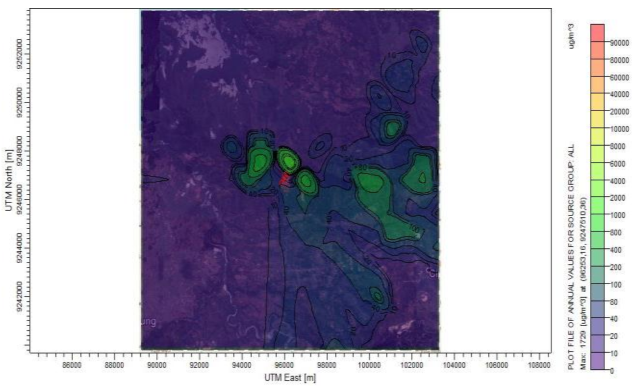
Based on the methane gas distribution map in Figure 8, it was observed that the maximum concentration was at the UTM coordinates of 96253.16 m, 9,247,510.36 m, which was close to the Sarimukti landfill. The area that had the maximum concentration was dominated by an open land with various vegetation, as exposure to methane gas did not have a significant impact on these plants.



(a) Period 1 Hour



(b) Period 24 Hours

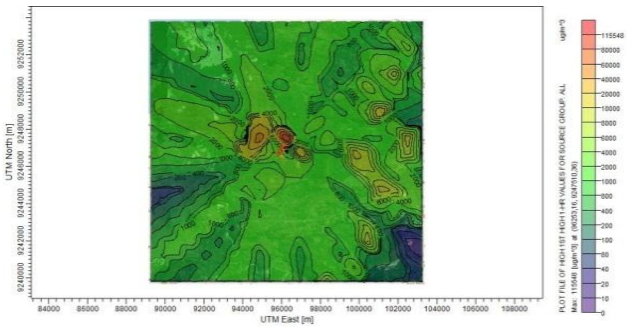


(c) Period 1 Year

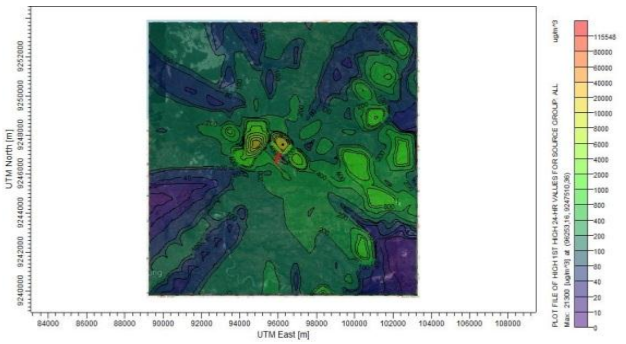
Figure 8. Map of Concentration Map of Methane Gas Distribution by IPCC Method 2006 Year 2025

3.4.3 Dispersion of Methane Emissions from LandGEM Method Data

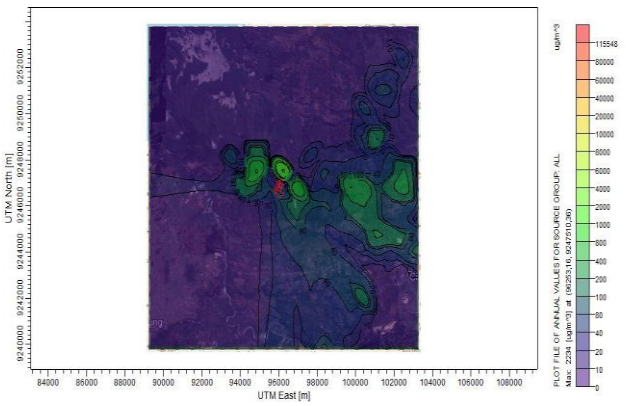
The following was an estimation of the distribution of methane gas, via the use of the LandGEM method. The results obtained for a period of 1 & 24 hours, as well as 1 year, were also observed in Figure 9 (a), (b), and (c), where the maximum methane gas distribution values were 115548 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), 21300 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), and 2234 μg/m^3 (at UTM 96253.16 m, 9247510.36 m), respectively.



(a) Period 1 Hour



(b) Period 24 Hours



(c) Period 1 Year

Figure 9. Map of the Concentration Map of Methane Gas Distribution by LandGEM Method in 2025

Based on Figure 9, it was observed that the maximum concentration in the distribution of methane gas was at the UTM coordinates 96253.16 m, 9247510.36 m, which was dominated by an open land with various plant vegetation.

3.5 Ozone Forming Potential

The calculation of this potential was used as a risk illustration of the Sarimukti landfill, which did not have methane gas utilization facilities. Also, the results regarding the potential of surface ozone formation from the concentration of CH_4 are presented in Table 10.

Table 10. Potential for Ozone Generation

Year	LandGEM Method	IPCC Method 2006	Maximum Incremental Reactivity (MIR)	OFP Methane Emission LandGEM Method	OFP Methane Emission IPCC Method 2006
	Methane Emission	Methane Emission	MIR Methane		
	Mg/Year	Mg/Year		Mg/Year	Mg/Year
2015	1052.40	1381.67		16.84	22.11
2016	2542.85	2681.74		40.69	42.91
2017	4020.78	3905.37		64.33	62.49
2018	5396.94	5057.37		86.35	80.92
2019	6716.08	6142.28		107.46	98.28
2020	8203.55	7164.34	0.016	131.26	114.63
2021	9632.68	8127.53		154.12	130.04
2022	11005.79	9035.57		176.09	144.57
2023	12325.05	9891.96		197.20	158.27
2024	13592.58	10699.97		217.48	171.20
2025	14810.41	11462.66		236.97	183.40

Table 10 was the result of calculations regarding the potential for surface ozone formation from the concentration of methane gas (CH_4) emissions, which was generated via the calculation of the IPCC Guideline 2006 and LandGEM methods. Based on the table, it was observed that the potential for surface ozone formation from methane gas emissions increased every year, which was dangerous for the environment. The highest potential for surface ozone formation from methane gas emissions was in 2025, at values of 183.40 Mg/year (IPCC 2006 method) and 236.97 Mg/year (LandGEM method). Also, higher surface ozone formation potentially contributed to global warming, as well as the threat to human health.

4 CONCLUSION

The methane gas emissions produced in Sarimukti landfill via the IPCC Guideline 2006 and the LandGEM methods in 2025, were 11462.66 Mg/year and 14810.41 Mg/year, respectively. It was also noted that the emission estimation via the method of LandGEM, consistently showed larger result than the IPCC. However, better representation of biological process occurred at the landfill. Among the two methods, LandGEM was selected to be the best, because of its use of the second orde formula in the equation used. Besides that, LandGEM calculated the age of waste and nutrients available for microorganisms. Meanwhile, the highest potential for surface ozone formation from methane gas emissions in Sarimukti landfill, was in 2025, with values at 183.40 Mg/year (IPCC 2006 method) and 236.97 Mg/year (LandGEM method), respectively.

Annual operation data are supposed to be obtained from the authority, as estimation on waste generation based on solely population data is likely to introduce bias, which should not to be significant. Further estimation of solid waste via dynamic model was also recommended, in order to incorporate many factors, which includes service area of the landfill, to reduce this bias.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the corresponding author.

ACKNOWLEDGMENTS

The authors would like to thank the KEMENRISTEKDIKTI for providing financial support. Furthermore, all relevant governmental agencies are acknowledged for useful data sharing.

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