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A Projection Study of Gaseous Pollutants Formed, Potential Health Effects and Clinical Codification in Piyungan Landfill

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ABSTRACT

The world is currently facing significant environmental challenges due to increasing urbanization and globalization. Human activities can produce greenhouse gases (GHGs) such as CO_2 and CH_4. One of the contributors to GHG generation is the open dumping of Municipal Solid Waste (MSW), particularly because much of the waste is organic. It undergoes anaerobic decomposition, leading to the formation of GHGs, particularly methane. However, CH_4 has a high potential for energy generation, and if harnessed properly, it can be highly beneficial. This study aims to assess the total air pollutants emitted from the landfill gas (LFG), including methane (CH_4), carbon dioxide (CO_2), and nonmethane organic compounds (NMOC) at the Regional Piyungan landfill in D.I. Yogyakarta province. The study also projected the year when the production of these gaseous pollutants would peak and when they are expected to be exhausted. Additionally, the study aimed to identify the potential health problems and clinical codification caused by these gaseous pollutants. To achieve these objectives, the LandGEM 3.03 version of the model developed by USEPA was used for the period 2023-2071. Clinical coding used the 2019 version of the ICD-10 reference. The estimated values for total LFG were 1.648E+04 (2024) and 1.584E+04 (2025) Mg/year, while CH_4 was estimated at 4.403E+03 (2024) and 4.230E+03 (2025) Mg/year. CO_2 was estimated to be 1,208E+04 (2024) and 1,161E+04 (2025) Mg/year, and NMOC was projected at 2,839E+01 (2024) and 2,727E+01 (2025) Mg/year. Some of the toxic effects that can occur cause respiratory, visual, and mental disorders with a variety of clinical codes.

INTRODUCTION

The Piyungan landfill is one of the overloaded landfills in Indonesia that will soon be closed. It is located in the Piyungan sub-district, Bantul Regency, and serves as a zoning site for waste collection from three cities: Sleman, Bantul, and Yogyakarta. The D.I. Yogyakarta government announced in a Circular Letter of the Regional Secretary of D.I. Yogyakarta number 658/8312 year 2023 that the Piyungan Regional landfill will no longer be able to accept waste from July 23, 2023, until September 5, 2023. This decision comes as a result of the daily incoming waste generation reaching an average of 450 tons. In 2022, the waste entering the Piyungan Regional landfill reached 97,086 $t.y^{-1}$ (Pemda Kabupaten Bantul 2022), while the landfill's total area is only 12.5 hectares. Out of this, 10 hectares are already used as landfills, and the remaining 2.5 hectares function as supporting facilities, including offices, workshops, weighbridges, and buffers (Ariyani et al. 2019). In addition, the waste managed at the Piyungan Regional landfill is only 4,951 tons per year, primarily through scavenger recovery. However, the waste management at the Piyungan Regional landfill is not optimal due to the damaged and poorly maintained leachate treatment plant (KLH 2023).

The quality of waste services in landfills is directly proportional to the existing infrastructure and the management of waste. When waste is left unmanaged in landfills, it can lead to various problems, one of which is the presence of hazardous landfill gas (LFG) pollutants. Methane gas (CH_4) and carbon dioxide (CO_2) are two groups of gases that can be found in landfills. It is estimated that municipal solid waste can produce approximately 50-60% CH_4 gas and 40-50% CO_2, respectively (Amini et al. 2012, Gasbarra et al. 2019). Gas production in landfills can occur due to anaerobic decomposition, evaporation, and chemical reactions from other processes (ASTDR 2023, Sonibare et al. 2019, USEPA 2023a, 2023b). Recent studies of landfills conducted in European countries revealed that about 20% of CH_4 from anthropogenic activities is attributed to municipal solid waste (MSW) undergoing processing in landfills (Delgado et al. 2023). Similarly, a recent report submitted by the USEPA observed that CH_4 from landfills in the US accounted for 17% of the total CH_4 generated (USEPA 2023a, 2023b). Studies in 2000 have projected that developing countries are responsible for 29% of total GHG, which is expected to increase to 64 and 76% by 2030 and 2050, respectively (Rafiq et al. 2018).

The Landfill Gas Emission Model (LandGEM) is a numerical model developed by the USEPA to project CH_4 at United States landfill sites. The use of the model has been used globally to assess CH_4 from various landfills after considering input values to represent appropriate site conditions. A study conducted at the rehabilitated La Gabarre waste dome estimated a total CH_4 of no less than 1.80 × 108 m^3 during the study period of 1995-2135 (Plocoste & Jacoby Koaly 2016). The study in Tirupati estimated a CH_4 concentration of 1.66 × 107 $m^3.y^{-1}$ in 2042 using the LandGEM model (Ramprasad et al. 2022). Studies at Benowo and Antang landfills showed that CH_4 at Benowo landfill in 2032 reached the highest value of 24,190 $Mg.y^{-1}$, and in 2030, at the Antang landfill, it was 123,900 $Mg.y^{-1}$ (Mahful & Managi 2018). The LandGEM model was also used to predict CH_4 in Sarimukti, West Java landfill. The highest result was in 2025 at 14,810.41 $Mg.y^{-1}$ (Wijaya et al. 2021). The study conducted between 2018 and 2047 in Muara Fajar Landfill 2 Pekanbaru City showed that the highest CH_4 emissions in 2047 amounted to 21,290 $Mg.y^{-1}$ (Betharia & Aryo Sasmita 2021). The accuracy of the predicted values in the model is highly dependent on the input parameters. Based on these considerations, some limited research has considered analyzing the uncertainty in CH_4 caused by the accuracy of input parameters (Ghosh et al. 2019, Srivastava & Chakma 2020). This study is conducted at the Regional Piyungan landfill. Considering the urgent problem of the landfill facing the closure of waste services, the study aims to achieve the following objectives: (a) Estimate the total air pollutants emitted from the LFG, CH_4, carbon dioxide, and nonmethane organic compounds (NMOC). (b) Project the year when the production of these gaseous pollutants reaches its peak and is expected to be exhausted. (c) Knowing potential health problems and clinical codification caused by these gaseous pollutants. This study will contribute to the projection of gaseous pollutants that could arise in the Piyungan Regional Landfill until 2071.

MATERIALS AND METHODS

Type and Design of Research

The research conducted in this study adopts an inquiry mode-quantitative approach to explore and quantify the concentration of LFG, CH_4, CO_2, and NMOC pollutants at the Piyungan Regional landfill for the upcoming year. Meanwhile, the study design utilized is reference period-prospective, aimed to estimate and project gas pollutants until the year 2071 using the LandGEM modeling approach. The data source for this study consists of secondary data obtained from various sources, including the National Waste Management Information System (SIPSN) of the Ministry of Environment and Forestry of the Republic of Indonesia, the Provincial Environment Office of D.I. Yogyakarta; World Health Organization (WHO)for clinical coding data; and database journals and government to determine the potential health risks that occured. The quantitative data used in this study pertains to the incoming waste for the years 2021, which was 98,436 $t.y^{-1}$, and 2022, which was 97,086 $t.y^{-1}$ (KLH 2023). To estimate the average incoming waste for the Piyungan Regional landfill, an assumption is made, and the average incoming waste is considered to be 97,761 $t.y^{-1}$. Additionally, the study utilizes rainfall data for D.I. Yogyakarta province, which indicates an average below 500 $mm.y^{-1}$ for the years 2018 and 2021, according to conventional classification (Buwono 2021, DLH Kota Yogyakarta 2018).

Data Analysis

This study employs mathematical modeling using the LandGEM software. The LandGEM modeling tool was developed by the United States Environmental Protection Agency (USEPA) to estimate landfill gas for sites located in the United States (Mou et al. 2015). The model was designed to predict uncontrolled occurrences at landfill sites and can project the resulting LFG over several years (Ramprasad et al. 2022). The advantage of this model is its flexibility in used inputs, making it a suitable choice for predicted LFG (Anh et al. 2022). LandGEM is one of the instruments that can be used to predict LFG from MSW at a study site. The instrument can be used to see the amount and composition of gases from organic matter degradation processes (Kale & Gökçek 2020, Sughosh et al. 2019). The equations used in the LandGEM (v3.03) model are shown in the following equations (Equation 1),

$$QCH4 = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL0 \left(\frac{Mi}{10}\right) e^{-ktij}$$

Equation 1. The Mathematical Modeling of LandGEM (v3.03)

Where,

QCH_4 = annual methane generation in the year of the calculation ($m^3.y^{-1}$)

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 ($m^3.Mg^{-1}$)

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

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

The accuracy of the LFG prediction value depends on the input parameters. However, determining various input parameters related to municipal solid waste (MSW) characteristics is often complex, and in many cases, suggested or default values are preferred. For instance, parameters like MSW_F, L_0, and K may be assigned specific values (Srivastava & Chakma 2020), where K varies between 0.04 and 0.06, and MSWF varies between 70% and 90%, with 80% being the default value (Ghosh et al. 2019, Srivastava & Chakma 2020). Using these suggested or default values can introduce uncertainties in CH_4 estimation, which require careful assessment.

RESULTS AND DISCUSSION

The SIPSN declared in 2021, the Piyungan Regional Landfill received incoming waste of 98,436 $t.y^{-1}$, and in 2022, it received 97,086 $t.y^{-1}$. Due to incomplete data on incoming waste from the establishment of the landfill in 1996, we used the last two years of data as an assumption of the average 97,761 $t.y^{-1}$ of incoming waste at the Regional Piyungan landfill (KLH 2023). The study projected the concentration of LFG from 2023 to 2071. Here are the results,

Table 1: The Projection Results of total LFG, CH_4, CO_2, NMOC Pollutants at Piyungan Regional Landfill 2023 to 2071

Year	Total Landfill Gas [$Mg.y^{-1}$]	Methane [$Mg.y^{-1}$]	Carbon Dioxide [$Mg.y^{-1}$]	NMOC [$Mg.y^{-1}$]
2023	1,616E+04	4,316E+03	1,184E+04	2,783E+01
2024	1,648E+04	4,403E+03	1,208E+04	2,839E+01
2025	1,584E+04	4,230E+03	1,161E+04	2,727E+01
2026	1,522E+04	4,064E+03	1,115E+04	2,620E+01
2027	1,462E+04	3,905E+03	1,071E+04	2,518E+01
2028	1,405E+04	3,752E+03	1,029E+04	2,419E+01
2029	1,350E+04	3,605E+03	9,891E+03	2,324E+01
2030	1,297E+04	3,463E+03	9,503E+03	2,233E+01
2031	1,246E+04	3,328E+03	9,130E+03	2,145E+01
2032	1,197E+04	3,197E+03	8,772E+03	2,061E+01
2033	1,150E+04	3,072E+03	8,428E+03	1,980E+01
2034	1,105E+04	2,951E+03	8,098E+03	1,903E+01
2035	1,062E+04	2,836E+03	7,780E+03	1,828E+01
2036	1,020E+04	2,724E+03	7,475E+03	1,757E+01
2037	9,800E+03	2,618E+03	7,182E+03	1,688E+01
2038	9,415E+03	2,515E+03	6,900E+03	1,621E+01
2039	9,046E+03	2,416E+03	6,630E+03	1,558E+01
2040	8,692E+03	2,322E+03	6,370E+03	1,497E+01
2041	8,351E+03	2,231E+03	6,120E+03	1,438E+01
2042	8,023E+03	2,143E+03	5,880E+03	1,382E+01
2043	7,709E+03	2,059E+03	5,650E+03	1,328E+01
2044	7,406E+03	1,978E+03	5,428E+03	1,276E+01
2045	7,116E+03	1,901E+03	5,215E+03	1,225E+01
2046	6,837E+03	1,826E+03	5,011E+03	1,177E+01
2047	6,569E+03	1,755E+03	4,814E+03	1,131E+01
2048	6,311E+03	1,686E+03	4,626E+03	1,087E+01
2049	6,064E+03	1,620E+03	4,444E+03	1,044E+01
2050	5,826E+03	1,556E+03	4,270E+03	1,003E+01
2051	5,598E+03	1,495E+03	4,102E+03	9,640E+00
2052	5,378E+03	1,437E+03	3,942E+03	9,262E+00
2053	5,167E+03	1,380E+03	3,787E+03	8,899E+00
2054	4,965E+03	1,326E+03	3,639E+03	8,550E+00
2055	4,770E+03	1,274E+03	3,496E+03	8,215E+00
2056	4,583E+03	1,224E+03	3,359E+03	7,893E+00
2057	4,403E+03	1,176E+03	3,227E+03	7,583E+00
2058	4,231E+03	1,130E+03	3,101E+03	7,286E+00
2059	4,065E+03	1,086E+03	2,979E+03	7,000E+00
2060	3,905E+03	1,043E+03	2,862E+03	6,726E+00
2061	3,752E+03	1,002E+03	2,750E+03	6,462E+00
2062	3,605E+03	9,630E+02	2,642E+03	6,209E+00
2063	3,464E+03	9,252E+02	2,539E+03	5,965E+00
2064	3,328E+03	8,889E+02	2,439E+03	5,731E+00
2065	3,197E+03	8,541E+02	2,343E+03	5,507E+00
2066	3,072E+03	8,206E+02	2,251E+03	5,291E+00
2067	2,952E+03	7,884E+02	2,163E+03	5,083E+00
2068	2,836E+03	7,575E+02	2,078E+03	4,884E+00
2069	2,725E+03	7,278E+02	1,997E+03	4,692E+00
2070	2,618E+03	6,993E+02	1,919E+03	4,508E+00
2071	2,515E+03	6,718E+02	1,843E+03	4,332E+00

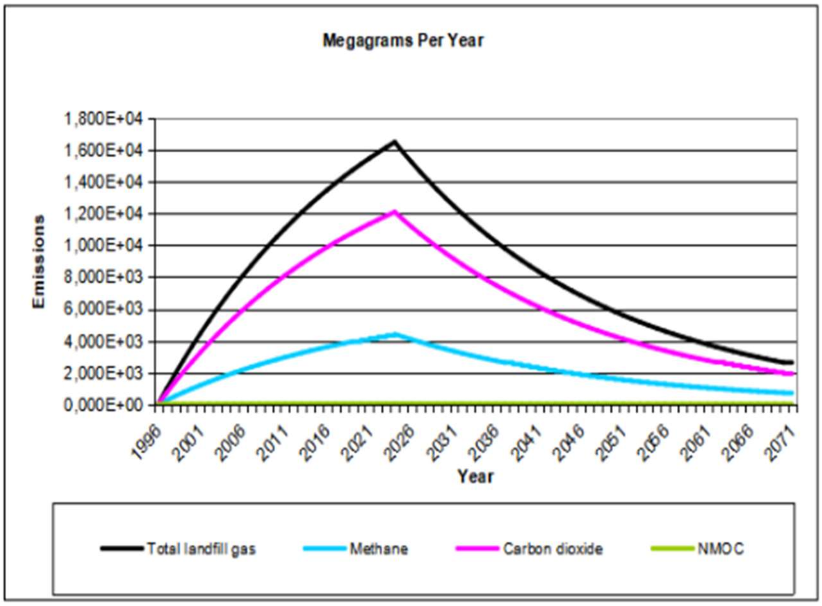

Fig. 1: The Estimation of gas existence in regional Piyungan landfill 1996 to 2071.

Previous assessments conducted for LFG estimation have published that, of the total LFG radiated, approximately 50% is CH_4, 45-50% is CO_2, and there are trace concentrations of NMOC (Aydi 2012, Saral et al. 2009). In the LandGEM (v3.03) assessment Table 1, there was no gas production recorded at the Regional Piyungan landfill in 1996 (DLH DI Yogyakarta, 2020). These gaseous pollutants reach their optimal production process in 2024. These gaseous pollutants will experience an optimal increase process from 2024 to 2025 and experience a trend of decreasing concentrations after 2026 (Fig. 1).

Based on the projection results, with the assumption that the Piyungan Regional Landfill experienced a temporary closure from July 23 to September 5, 2023, the estimated CH_4 generation rate was 0.04 year-1. The value of L_0 (potential methane generation capacity) is 100 $m^3.mg^{-1}$, while NMOC is estimated at 600 ppm as hexane, with a CH_4 content of 50% by volume. It is essential to note that these values come with a level of uncertainty, as they depend on factors such as the amount of incoming waste (MSW_f) and rainfall (k and L_0), with D.I. Yogyakarta Province classified as inventory conventional (k = 0.04). A parallel study conducted in Kapur City, India, found that uncertainties in the value of K (ranging from 0.04 to 0.06) resulted in variations in CH_4, around 233.44 to 350.16 in total LFG; 116.75-175.13 in CH_4 and CO_2; and 0.93-1.395 $Mm^3.y^{-1}$ in NMOC generation (Chandra & Ganguly 2023). Similarly, a study at a landfill site in Delhi, India, also revealed large variations in CH_4 due to uncertain values of MSW_F and k in LFG (Srivastava & Chakma 2020). These uncertainties emphasize the importance of accurately determining input parameters to improve the reliability of CH_4 estimations from landfills.

The active zone in the Piyungan Regional Landfill is not entirely closed, leading to the decomposition of organic waste by microorganisms and the production of gaseous pollutants (Rajesh et al. 2020). Additionally, the non-functional leachate treatment plant results in the generation of leachate from landfill activities, primarily influenced by rainfall, surface water from the surrounding environment, and the decomposition of waste in the landfill. As leachate filters through the waste, it leaches out certain chemicals from the waste pile, leading to concerns about rising odor levels, groundwater contamination, and insect breeding grounds (Teng et al. 2021). Studies have shown that leachate generated from open dumpsites can cause groundwater to exceed permissible limits for physicochemical parameters and heavy metals, with water quality improving further downstream from the dumpsite (Sharma et al. 2020). Landfill operations generate a lot of toxic gaseous pollutants that have the potential to harm public health (Njoku et al. 2019). The presence of trash, dust, rodents, and the potential for unexpected fires are other risk factors present in landfills (Manheim et al. 2021). LFG can kineticize to the subsurface. Then, the gas builds up through the groundwater and soil. They eventually kineticize to the top surface. Fractures or other pathways in the subsurface can be a contributing factor to gas formation (Fay et al. 2011).

Total LFG, CH_4, CO_2, and NMOC have toxic effects that can cause health problems. We have collected data on the health risks that can occur due to these gases from the websites of health departments of several countries and journals. The data is presented in Table 2 using ICD 10 version 2019.

The toxic effects of CH_4 in Table 2 may occur because the presence of CH_4 in the air is greater than the availability of oxygen. The toxic effects of CH_4 in Table 2 may occur because the presence of CH_4 in the air is greater than the availability of oxygen. Methane gas, when concentrated in high amounts, can displace oxygen in the air. As a result, exposed people may experience oxygen deprivation or hypoxia. This hypoxia can cause cells in various parts of the body, including cells in the lungs, to not get enough oxygen to perform their normal functions (Hsieh & Chiou 2014). Methane is an irritant to the respiratory tract. Exposure to this gas can irritate the mucous membranes of the bronchi and bronchioles, which can stimulate an inflammatory response and produce mucus (Chien et al. 2017, Zhang et al. 2019). This can result in symptoms such as coughing, breathlessness, and increased mucus production. High methane exposure can cause inflammation of the lung tissue. This inflammatory process can affect the normal functioning of the lungs and cause symptoms such as chest pain, coughing, and difficulty breathing (Guo et al. 2012, Mo et al. 2017). High methane exposure can lead to a build-up of gas in the lung spaces, which can obstruct airflow and cause airway blockage. This can lead to symptoms such as significant breathlessness. Due to the lack of oxygen, the body may respond by increasing the rate of breathing (hyperpnoea) to try to increase oxygen uptake. This can lead to respiratory fatigue and increased workload on the respiratory system. Exposure to methane gas can also trigger oxidative processes in lung cells, which can damage cells and cause oxidative stress (Lin et al. 2013, Zhang et al. 2018). This damage can exacerbate inflammation and be detrimental to lung function. Poor respiratory conditions, such as prolonged oxygen deprivation, can have systemic effects on other organs in the body. This can lead to serious health complications, including disorders of the cardiovascular and nervous systems (Chen et al. 2013, Wellenius 2012).

While CO_2 comprises 40-60% of landfills, the denser-than-air nature of CO_2 will cause the gas to collect in confined spaces such as leachate impoundments. People in communities near the landfill are often concerned about the odor emitted from the landfill. They say that these odors are the source of undesirable health effects or symptoms, such as headaches and nausea (Henrotin et al. 2010). At low-level concentrations - usually associated with landfill gas - it is unclear whether it is the concentration itself or the odor that triggers the response (Miller et al. 2007). Typically, these effects diminish when the odor is no longer detectable. Bacterial or chemical processes produce landfill gas odors and can come from active or closed landfills.

These odors can migrate to surrounding communities. Potential sources of landfill odors are NMOCs (vinyl chloride and hydrocarbons) if present at high enough concentrations. Many NMOCs have irritant properties to the respiratory tract. High exposure may irritate the mucous membranes in the respiratory tract, which may result in symptoms such as coughing, shortness of breath, and chest discomfort (Ferguson et al. 2017, Yorifuji et al. 2013). Some NMOCs can have direct toxic effects on lung cells. This can cause inflammation and cell damage, resulting in impaired lung function and leading to more serious respiratory symptoms (Chung et al. 2017, Lee et al. 2014). The disposal of certain types of waste, such as manure and fermented grains, can also generate landfill odors.

Table 2: Possible health risks and clinical codifications that may result from exposure to total LFG, CH_4, CO_2, and NMOCs in Landfills.

Pollutants	Possible Health Risks	Possible Clinical Codifications
CH_4	CH_4 is a precursor of ozone (O_3). CH_4 does not enter directly but through exposure to ozone. Exposure to ozone can cause chronic obstructive pulmonary disease (COPD), impaired lung function, and asthma.	1. Sub-category J44 other chronic obstructive pulmonary disease and its derivatives 2. Sub-category J06 (acute respiratory infection) and J18 (pneumonia) 3. Sub-category J45 asthma and its derivatives (Forouzanfar et al. 2015, Turner et al. 2016, Van Dingenen et al. 2018, Zhang et al. 2019)
CO_2	CO_2 concentrations of 10% or more can cause unconsciousness and death. Meanwhile, lower concentrations can cause sweating, headache, tremors, headache, rapid breathing, increased heart rate, shortness of breath, mental depression, dizziness, and visual disturbances.	R51 headache and its derivatives R25.1 tremor unspecified and its derivatives F32.9 depressive disorder H53-H54 visual disturbance and its derivatives (ATSDR 2001)
NMOC	NMOCs such as vinyl chloride and hydrocarbons are included in odors that can disrupt sleep and frustrate stress.	Sub-category T59 (toxic effect of other gases, fumes, and vapors) complicated by biochemical evidence of fetal stress (ATSDR 2001)

One of the main limitations of this study is the use of assumptions regarding the incoming waste at the Regional Piyungan landfill in 2021 and 2022, obtained through the SIPSN. The incoming waste data may be complete from 1996 to 2022, allowing for a more accurate projection of outgassing results using this refined value in the LandGEM model. Furthermore, the determination of conventional inventory rainfall categories (k and L0) relies on a study conducted by the Environmental Agency of D.I. Yogyakarta province in 2018 and 2021 due to limited access to rainfall data, which ideally should use justifications from the last 5 to 10 years to ensure better accuracy.

CONCLUSION

The landfill gas generation at the Regional Piyungan landfill in D.I. Yogyakarta province was estimated using the LandGEM model version 3.03. The study shows that these gaseous pollutants will experience an optimal increase process from 2024 to 2025 and will subsequently exhibit a trend of decreasing concentrations after 2026. The estimated values for total landfill gas are 1.648E+04 and 1.584E+04 $Mg.y^{-1}$ for the respective years, while CH_4 gas is estimated at 4.403E+03 and 4.230E+03 $Mg.y^{-1}$. Carbon dioxide is estimated to be 1.208E+04 and 1.161E+04 $Mg.y^{-1}$, and NMOC is projected at 2.839E+01 and 2.727E+01 $Mg.y^{-1}$. These findings suggest that high LFG, particularly CH_4, significantly impacts the ambient air quality of D.I. Yogyakarta province. The gas has varied toxicity and clinical codification, with possible health problems such as respiratory system disorders, vision, and mental disorders. The study also underscores the importance of accurately determining input parameters for predicting CH_4, as even small variations can result in significant uncertainties. Furthermore, the study highlights the potential for energy recovery from the CH_4 generated in landfills. By harnessing the energy generated from MSW in D.I. Yogyakarta province, CH_4 can be significantly reduced while simultaneously serving as a valuable local energy source.

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