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RESEARCH ARTICLE

SEASONAL VARIATION OF METHANE CONCENTRATION AND EMISSION INTENSITY FROM BANTARGEBANG LANDFILL, INDONESIA

Maulanie Makhardani

1. Student, Department of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China.

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Abstract

Landfill methane emissions are a significant contributor to greenhouse gas emissions that cause global warming, especially in developing nations like Indonesia that produce a lot of organic waste. The climate around the landfill has a big impact on the pattern of methane gas release into the atmosphere. This study aimed to analyze the spatial distribution of methane gas from the BantarGebang landfill by season in 2023 using Sentinel-5P and to examine its relationship with meteorological factors in the landfill area.The results showed that the average methane concentration during the rainy season was 1779.6 ppm and increased to 1817.4 ppm during the dry season. The plume moves southward during the rainy season, whereas gas gathers closer to the emission source during the dry season. Weather-related variables, such as wind and rainfall, affect this.This study shows that Sentinel-5P is effective in detecting seasonal methane patterns in tropical regions and supports methane gas management strategies, including the implementation of Landfill Gas-to-Energy (LFGE) and monitoring, Reporting, and Verification (MRV) systems in order to achieve the 2030 Nationally Determined Contribution (NDC) targets.

Introduction:-

Methane (CH4) is a greenhouse gas that has a global warming potential approximately 28 times greater than CO2 in a 100-year time horizon (IPCC) (Lorente et al., 2021). One source of methane gas is landfills, where anaerobic decomposition processes produce landfill gas (LFG) (Olaguer et al., 2022). As shown in Table 1, LFG is dominated by methane gas, approximately 40-70%, which if the gas is not managed properly will be released into the atmosphere and accelerate the accumulation of greenhouse gases(Riman et al., 2022).

Table 1. Landfill Gas Composition (EPA, 2025; Themelis and Ulloa, 2007)

Component	Concentration Range (%)
Methane	40-70
Carbon Dioxide	30-60
Carbon Monoxide	0-3

Corresponding Author:-Maulanie Makhardani
Address:-Student, Department of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China.

Nitrogen	3-5
Oxygen	0-3
Hydrogen	0-5
Hydrogen Sulfide	0-2
Trace compounds	0-1

Currently, the development of remote sensing technology, such as the Sentinal-5P satellite equipped with the Tropospheric Monitoring Instrument (TROPOMI), has opened up great opportunities to monitor methane concentrations, from global to local with high spatial and temporal resolution (Lorente et al., 2021). Through infrared spectroscopy, which identifies the areas of greatest temperature from sources, this TROPOMI can gauge the total dry air methane (XCH4) content (Maasakkers et al., 2022). Studies have demonstrated that this product from TROPOMI has a high degree of consistency over time and a low random error (0.1%) that is suitable for tracking seasonal and spatial changes (Lindqvist et al., 2024).

Population and consumption are both significant factors in the increasing generation of municipal waste, as is the case with Indonesia. For instance, the BantarGebang landfill in West Java Province is Indonesia's largest landfill, it has a daily capacity of 7,000-8,000 tons of waste and is responsible for the majority of the release of methane in the Jakarta area (Yulianto et al., 2024). The study by Riman et al. (2022), shows that methane emission intensity may vary seasonally due to different meteorological conditions like humidity and temperature, including all activities of methanogenic microbes in tropical countries.

Factors related to meteorology, such as temperature, humidity, precipitation, and wind velocity, can have an effect on the creation and release of methane from waste disposal sites (Pendergrass et al., 2025). High humidity and precipitation can enhance the anaerobic degradation of methane and the wind can affect the transmission and distribution of the gas in the atmosphere(de Jong et al., 2025). Therefore, analyzing the relationship between meteorological parameters and the spatial distribution of methane concentration is crucial for understanding the year-round emission dynamics in tropical regions (Nesser et al., 2024).

Satellite data combined with local secondary data will open up an opportunity to understand more comprehensively methane emissions from landfills (Olaguer et al., 2022). The TROPOMI data can be employed to measure the concentration of methane near the BantarGebang landfill, additional data can be employed to determine the causes of these variations in concentration (Lindqvist et al., 2024; Maasakkers et al., 2022).

This study intends to observe the spatial variability of methane concentration by season over Indonesia, to analyze the relationship between meteorological factors and patterns of methane, and also to evaluate environmental and management implications for landfill management in tropical regions. Thus, this study aims to further scientific knowledge in the areas of greenhouse gas management in the waste industry, satellite-based monitoring, and the seasonal dynamics of methane emissions in densely populated tropical ecosystems.

Methodology:-

Study Area:

This research was conducted at the BantarGebang Landfill in Bekasi City, Indonesia. This landfill was chosen because it is one of the largest landfills in Indonesia, covering an area of approximately 110 hectares and capable of accommodating 7,000-8,000 tons of waste daily from the DKI Jakarta region (Yulianto et al., 2024). Indonesia has a humid tropical climate with two seasons: the rainy season from November to April, and the dry season from May to October. Meteorological factors such as rainfall, temperature, humidity, and wind speed play an important role in determining the anaerobic decomposition process in landfills, which produces methane emissions (Riman et al., 2022).

Data Sources:

The Sentinel-5 Precursor (Sentinel-5P) data is derived from the Tropospheric Monitoring Instrument (TROPOMI) which is maintained by the European Space Agency (ESA). This Sentinel contains a dry-air methane (XCH_4) data product that is derived from the NASA website Giovanni, this product is then outputted in NetCDF format. The information utilized in this research is from the time period from January to December of 2022 with a resolution of approximately 0.05° x 0.05° (approximately 5.5 km), which allows the regional scale to be observed (Lorente et al., 2021).

Additionally, this information employs a quality assurance value (qa_value) of 0.5, as recommended in the Sentinel-5P user manual - methane (CH4) and the S5P Methane Product Dataset File (Apituley et al., 2022; SRON and BIRA-IASB, 2025). This dataset was then split into two separate seasons, the rainy season and the dry season, in order to assess the differences in the distribution of CH4 between seasons (Lindqvist et al., 2024). TROPOMI was selected because of its high degree of sensitivity to changes in CH4 concentrations in the lower atmosphere, this made it effective at detecting sources of methane in urban areas and landfills (Vanselow et al., 2024).

Other important data included data from the local meteorological agency, which was obtained from the database of the Meteorology, Climatology, and Geophysics Agency (BMKG) at Kemayoran in Jakarta, for the meteorological conditions in the area in 2023, including the air temperature, relative humidity, rainfall, and wind speed (BMKG, 2024). Additionally, information regarding the composition and volume of waste in BantarGebang was derived from various national and international sources

Data Visualization and Processing:
The Sentinel-5P satellite data was interpreted using the Panoply v55.1 software, which is developed by the Goddard Institute for Space Studies (GISS). Panoply was employed in this research because it possessed a simple graphical interface that demonstrated multiple atmospheric data dimensions without necessitating advanced statistical analysis (Follette-Cook and Gupta, 2019). Also, Panoply supports the multidimensional visualizations with various map projections, including color mapping and geographic overlays that are intended to facilitate spatial analysis (Kavats et al., 2022).

This analysis was conducted using a descriptive-spatial approach, the purpose of which was to observe differences in patterns of distribution, areas of high intensity, and the direction of distribution of methane. This visual approach was employed because it can demonstrate the seasonal pattern of CH_4 in tropical regions without necessitating the use of computational models or algorithms. A similar approach was employed by Magro et al. (2021), who studied the behavior of CH4 and CO in response to extreme forest fires in Portugal using Sentinel-5P data and visualized using Panoply to identify changes in space for greenhouse gases. Other investigations have been conducted to observe the temporal changes in atmospheric gases without utilizing advanced statistical methodology (Kathiroli et al., 2023).

Research Limitations:-
This research used a descriptive-spatial methodology, depending on Sentinel-5P data without any statistical analysis or field validation. This method was used because there was a lack of insitu data in the BantarGebang waste area throughout the year of observation.

The examination of seasonal variations and the CH_4 distribution was mostly performed via visual map interpretation and the comparison of mean values between seasons. This method provides a full picture, but it doesn't show how meteorological data are related to each other in a way that is easy to understand.
Even with these problems, this method is nevertheless often used in preliminary remote sensing investigations of tropical trash emissions. The results may provide a foundation for further study necessitating field validation or a more comprehensive statistical examination.

Result:-
Seasonal Variation of CH4 Concentration:
The rainy season (November-April) and the dry season (May-October) are the two primary seasons in the tropical climate zone that includes the BantarGebang landfill area. Table 2 shows the variations in air temperature (33.8-35.2 degrees Celsius), relative humidity (95-100%), wind speed (2.4-3.1 kilometers), and the monthly amount of rainfall (35-604 mm^3) that occur between the two seasons.

Figure 1(A–B) illustrates the considerable variation in CH_4 concentration between the two seasons based on observations from the Sentinel-5 Precursor (TROPOMI) shown using NASA Panoply v5.5.1. During the rainy season, the average concentration of CH_4 was 1779.6 ppm, whereas during the dry season, it was 1817.4 ppm, a difference of over 37.8 ppm.

The color bar in the map represents methane concentration from low (blue) to high (red) and measured in ppm.The primary dark blue color on the rainy season's map is associated with lower concentrations, whereas the orange-red color during the dry season is indicative of a significant increase. The frequency of methane's production from landfills is directly affected by the temperature and humidity levels, which is observed in this increase (Kathiroli et al., 2023; Magro et al., 2021).

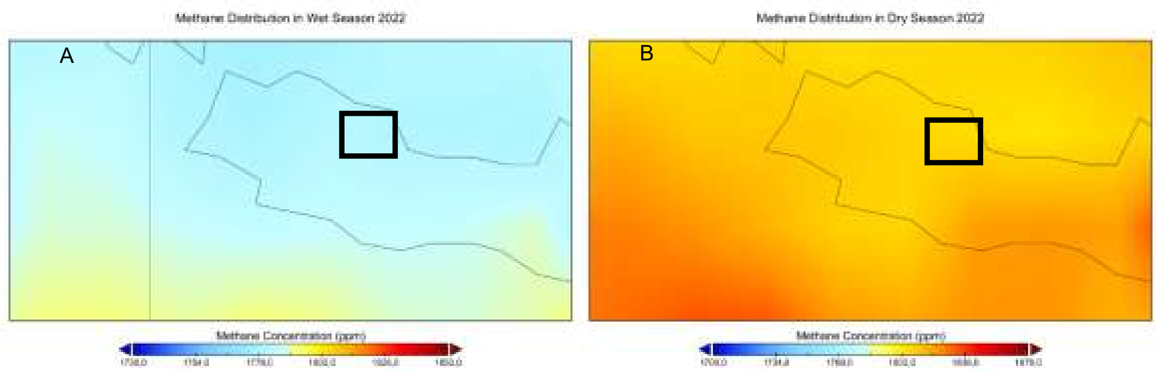

Figure 1. Methane Distribution in Landfill Area Based on Seasons, Wet Season (A); Dry Season (B)

However, CH_4 builds up more around emission source locations during the dry season due to increased stability in the atmosphere and decreased both horizontal and vertical mobility brought on by little rainfall (Silva et al., 2025). The comparatively low wind speed (2.5–3.1 knots), which permits the creation of tiny hotspots or high-intensity areas, lends additional credence to this scenario(Pendergrass et al., 2025).These findings show how well the Sentinel-5 P TROPOMI remote sensing instrument works as a temporal monitoring tool to assist greenhouse gas mitigation plans at waste management facilities in Indonesia.

Table 2. Meteorological Conditions in the Landfill Area (Government of DKI Jakarta, 2022)

Time		**Temperature (^oC)**	**moisture (%)**	**Wind Speed (knots)**	**Volume of Rainfall (mm^3)**
Wet Season	Nov	34.6	100	3.1	134.1
	Dec	34.2	98	2.5	171.6
	Jan	34.2	100	3.1	332.8
	Feb	34.0	98	3.8	604.4
	March	33.8	97	3.2	244.1
	April	34.2	100	2.9	213.9
Dry Season	May	34.8	98	2.6	203.6
	June	35.2	97	2.5	79.1
	July	34.6	95	2.4	35.8
	August	34.3	98	3.1	79.7
	Sep	35.0	97	2.7	113.4
	Oct	34.2	95	2.6	182.1

Spatial Distribution of Methane Around the Bantar Gebang Landfill:-

The mapping of space based on Sentinel-5P TROPOMI imagery shows the distribution of atmospheric methane (XCH_4) across Java, the capital region of Indonesia, and the BantarGebang landfill, both of which are indicated by a small black box on the map (Figure 1). During the rainy season (Figure 1A), light blue to yellow colors(indicates moderate amount of methane as shown on color bar) are the most common color spectrum in Java, the majority of the state's land surface is covered by this color, this indicates that the CH_4 plume is typically displaced southward due to the combination of seasonal northeasterly winds and high precipitation.

This condition is in agreement with data from the BMKG's Kemayoran (2023) that reported that the Asian wind pattern associated with the monsoon moves from northeast to southwest during the wet period, this causes the methane to follow the pattern of travel to the southern region of Java (Kusumaningtyas et al., 2024).During the dry season (May-October), the distribution pattern is primarily affected, the color of the orange is expanded over the northwest of Java, including the area of Jakarta, this indicates a significant increase in the concentration of CH_4 in the atmosphere.

This condition is caused by a decrease in wind speed (2.5-3.1 knots) (Table 2) and an increase in atmospheric stability, which both slow down the horizontal and vertical transport of gas. With increasing air temperatures (around 34-35 °C) and decreasing humidity, the gas methane derived from human activity and landfills in the Greater Jakarta region is typically stored in the upper atmosphere. A similar phenomenon was reported by Tu et al. (2022), in Madrid and Silva et al. (2025), in Caieiras Landfill, Brazil, during the dry period, the CH_4 plume was still elevated above the emission source because of the weakened dispersive force.

In the wet months, the CH_4 plume is displaced much more to the south than in the dry months due to increased migratory birds. Also, during wet months methane is concentrated from northern parts of Java where urban centers and waste sites are located. Therefore, regional climate variability controls not only gas horizontal transport but also the degree of methane build-up in a local atmosphere.

These regional differences indicate that the increase in CH_4 near the Jakarta area is the result of a combination of effects from both urban emissions and large landfills like BantarGebang, rather than a singular cause. (Dasgupta et al., 2022) states that satellite-based monitoring, such as Sentinel-5 P TROPOMI, is effective in recognizing methane hotspots in the region and supporting policy mitigation efforts. As such, these findings demonstrate that satellite data-based meteorological analysis of space can be employed to scientifically evaluate the release of CH_4 and to plan for the mitigation of greenhouse gases in areas with a high concentration of people in Indonesia.

Environmental Implications and Management:-

The composition and characteristics of the waste have a direct effect on the possibility of methane (CH_4) formation at the BantarGebang Landfill. According to Table 3, food waste, which is high in organic matter that decomposes quickly, accounts for about 39% of all waste. Plastic and cellulosic-lignin fractions, which include paper and wood, come in second and third, respectively, at 33%. Methane is the major component gas of high organic content during the anaerobic phase at landfills. This is high in organic content, therefore, it enhances the activity of methanogenic microorganisms (Chan et al., 2023).

Table 3. Waste Composition in BantarGebang Landfill

Waste Composition	Percentage (%)
Food waste	39
Plastics	33
Fabric	9
Wood	4
Paper	4
Toxic and hazardous	4
Rubber & leather	3
PET	2
Others	2

Table 4 contains information on waste having a density of 0.2 kg L^{-1} at BantarGebang, with 10.39% moisture content and a calorific value of 1373 kcal kg^{-1}. It is also wet and tends to break down chemical compounds (Gebert et al., 2022). The landfill can be considered one of the major sources in the tropics accounting for CH_4 emissions due to high organic content together with moderate moisture.

Table 4. Waste Characteristics

Characteristics	Value
Density	0.2 kg/L
Water content	10.39%
Heat value	1373.12 Kcal/Kg
Volatile Matter	326.61%

The volume of methane released by Jakarta is shown spatially in Figure 2. The total CH_4 volume from all landfills in Jakarta is 1,513.8×10 3 tons of CO2-equivalent year^{-1} with West Jakarta accounting most (433.4×10 3 tons of CO2-equivalent year^{-1}). This value demonstrates the predominance of populated areas that have high levels of waste production and limited systems for gas capture. The trend follows the pattern detected by Sentinel-5P TROPOMI imagery, northwestern part within city boundary has more intensive atmospheric CH_4 due probably to lack wind and large number landfills area.

The environmental implication of this pattern is that it increases the risk of CH_4 accumulation on the surface, then and there ready for spontaneous fires to significantly contribute to short-lived climate pollutants (SLCPs) (Vanselow et al., 2024). Integrated mitigation measures are necessary-in optimizing gas capture systems, effective flares, and using landfill gas to produce energy (LFGTE)-to reduce hence effects.

Test results from BantarGebang WTE pilot project indicate possible production of 12-16 million watts electricity through conversion of methane into energy (Agatha et al., 2024). A LFGTE system is also estimated would decrase the release of GHG by over 60% (Syarifuddin et al., 2023)

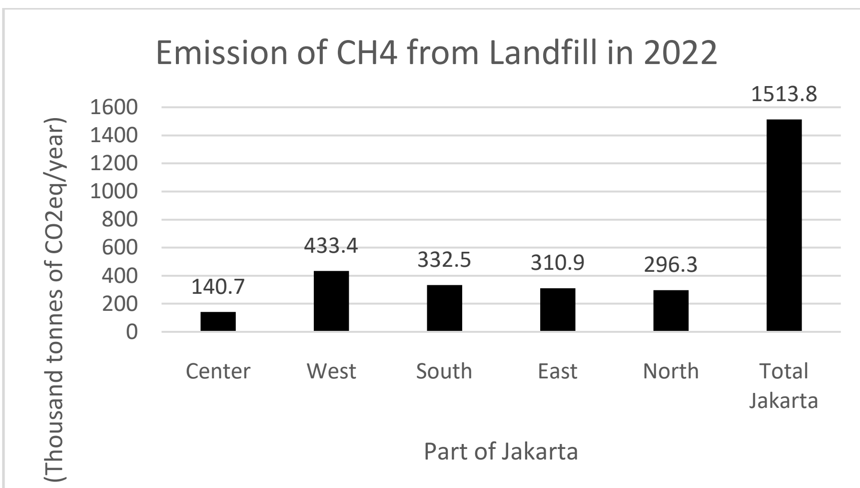

Figure 2. Emission of CH4 from Landfill in Jakarta Province

Besides that, covers are also very crucial. Compost-based bio covers or even stabilized soil enhance the biological conversion of CH_4 to CO2, with >90% success rate (Chan et al., 2023; Scheutz et al., 2023). These initiatives can be combined with moisture management through leachate recycling to keep constant microbial activity during the dry season (Gebert et al., 2022)Remote sensing-based monitoring (Sentinel-5P TROPOMI) can also be utilized as a Monitoring-Reporting-Verbatim (MRV) instrument which supports regional emission control policies. Hotspot automatic detection helps to prioritize landfills in improvement interventions during periods of most CH_4 concentrations (Dasgupta et al., 2022; Vanselow et al., 2024). The combination of satellite data and field trips (OGI drones or soil-flux chambers) will also increase the believability of national GHG statistics. Table 5 provides a summary link between observed results, environmental impact, and recommended management practice for the BantarGebang landfill.

Table 5. Summary of key methane–related findings, environmental implications, and recommended mitigation strategies at the studied landfill.

Aspect	Findings (from Results)	Environmental Implications	Recommended Strategy
Seasonal CH_4 Variation (4.1)	CH_4 average: Rainy 1779.6 ppm → Dry 1817.4 ppm	Higher flux in dry season due to reduced dispersion	Inspect cover before dry season; maintain moisture via leachate recirculation
Spatio-regional Distribution (4.2)	CH_4 plume southward in wet season; accumulates near landfill in dry season	Atmospheric accumulation & air-quality risk	Add gas wells & flares; enhance vegetation barrier
Waste Composition (4.3)	39 % food waste and volatile organic fraction	High methanogenic potential	Enhance organic waste segregation & composting
Landfill Cover Condition	Open work-face & poor sealing areas	CH_4 leakage & explosion risk	Apply biocover/biofilter; daily cover with compacted soil
Methane Capture & Utilization	Limited gas collection capacity	Unrecovered CH_4 adds to GRK	Expand LFGTE systems
Monitoring & Verification (MRV)	CH_4 pattern detected via Sentinel-5P	Supports hotspot tracking & policy targeting	Integrate satellite data with in-situ monitoring

Hence, the combination of dominant organic waste characteristics, observed regional emission patterns, and pertinent local meteorological conditions emphasize the necessity of an integrated approach to pollution management. Such practice can be considered prototype implementation of sustainable methane emission management at BantarGebang landfill as well as other landfills in Indonesian urban areas that biocover technology and active gas collection shall be applied together with satellite-based monitoring.

Conclusion:-

This study uses Sentinel-5P TROPOMI satellite data, secondary meteorological data, and waste characteristics to look at how methane (CH_4) levels change with the seasons and where they are at the BantarGebang landfill. During the dry season, the amount of CH_4 is higher (1,817.4 ppm) than during the rainy season (1,779.6 ppm). This is due to high temperatures, low humidity, and moderate wind speeds, which limit gas dispersion.Spatially, CH_4 plumes tend to spread southward during the rainy season and accumulate in the area around the landfill during the dry season, demonstrating the influence of monsoon winds and tropical atmospheric stability. The majority of the trash's composition is organic (39 percent food waste), its easily degradable properties increase the probability of methane production. The total emissions from the landfills in Jakarta's urban areas amount to 1.51 million tons of $CO2$-eq per year, which underscores the necessity of mitigation in urban areas with dense populations.

This method of using remote sensing to keep an eye on methane emissions in tropical landfills has worked well, and it could be used as a model for managing similar facilities in Indonesia in a way that is good for the environment.
The importance of putting integrated management strategies into practice—such as optimizing gas capture and flaring efficiency, biocoverage, and landfill gas utilization—is emphasized by this study. Together, field visits and Sentinel-5P satellite surveillance can improve the system's performance and assist the nation in achieving its greenhouse gas emission reduction targets.

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