Methane (CH4) and Carbon Dioxide (CO2) Concentration Monitoring System at Wonorejo Compost Center

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ABSTRACT

Composting of organic waste can generate greenhouse gases, such as methane (CH_4) and carbon dioxide (CO_2), which may affect environmental quality and public health. This study aims to design and implement an Internet of Things (IoT)-based monitoring system for CH_4 and CO_2 concentrations at Wonorejo Kompos Center. The system utilizes an ESP32 microcontroller integrated with MQ-4 and MQ-135 gas sensors. Measurement data are displayed on an LCD and transmitted to cloud-based storage via a WiFi connection. Data collection was conducted over 2 weeks with a 4-hour measurement interval. The results indicate that the average CO_2 concentration was approximately ± 106 ppm, while CH_4 concentrations ranged from 0.01 to 0.09 ppm. Comparison with Gas Chromatography (GC) laboratory analysis shows differences in absolute values; however, the IoT system consistently captures gas concentration trends. This system demonstrates potential as a real-time greenhouse gas monitoring solution in organic waste processing facilities.

Contribution to Sustainable Development Goals (SDGs):
SDG 11: Sustainable Cities and Communities
SDG 12: Responsible Consumption and Production
SDG 13 : Climate Action

1. INTRODUCTION

1.1. Research Background

The management of organic waste through composting is an important strategy for reducing the burden on final processing sites (TPA) while supporting the concept of sustainable development. According to data from the Ministry of Environment and Forestry [7], organic waste still accounts for the majority of Indonesia's waste generation, underscoring the need for an effective, environmentally friendly management system. One widely used method is composting, which reduces waste volume while producing beneficial products that improve soil quality. However, the decomposition process of organic materials in composting involves several challenges, including slow decomposition rates, high moisture content, and the presence of pathogens. One widely used method is composting, which can reduce waste volume while producing beneficial products that improve soil quality. However, the decomposition of organic materials during composting can produce greenhouse gases, particularly methane (CH_4) and carbon dioxide (CO_2). CO_2 gas is produced from the respiration process of aerobic microorganisms, while CH_4 gas is generally formed under anaerobic conditions due to the activity of methanogenic microorganisms [1].

Methane has a global warming potential approximately 28–34 times greater than CO_2 over 100 years, so even though its concentration is relatively small, its presence still has a significant impact on global climate change [6]. In addition to affecting the global environment, the accumulation of CH_4 and CO_2 in waste treatment facilities can degrade local air quality and pose health risks to workers and the surrounding community. Therefore, regular monitoring of gas concentrations is an important aspect of composting facility management to ensure that the process runs safely and in a controlled manner.

The development of Internet of Things (IoT) technology offers significant opportunities for real-time monitoring of environmental parameters at relatively low cost. IoT technology enables the integration of sensors, microcontrollers, and internet networks to continuously collect, transmit, and display environmental data remotely [2]. IoT-based monitoring systems have been widely developed to monitor hazardous gases, air quality, and other environmental parameters, offering high flexibility and efficiency. Based on this background, this study aims to design and implement an Internet of Things (IoT)-based monitoring system for methane (CH_4) and carbon dioxide (CO_2) gas concentrations at the Wonorejo Compost Center. This system is expected to provide real-time gas concentration information, capture gas emission trends during the composting process, and serve as an alternative environmental monitoring solution to support greenhouse gas emission mitigation efforts at organic waste processing facilities [8].

1.2. Literature Review

1.2.1. Internet of Things (IoT)

The Internet of Things (IoT) is a network of devices connected via the internet to collect, process, and share data in real time. In the context of environmental management, IoT can be used to monitor parameters such as temperature, humidity, and hazardous gas concentrations across various locations. Research by [2] states that IoT technology can increase the efficiency and accuracy of environmental monitoring by up to 85% compared to manual methods. IoT uses smart sensors connected to a cloud-based platform to process data and automatically notify when certain parameters exceed safe thresholds. With the implementation of IoT at landfills, gas emissions such as methane and ammonia can be continuously monitored, enabling early intervention to reduce their impact on the environment and public health. The concept of the Internet of Things (IoT) involves connecting physical devices to the internet to collect data, communicate, and perform actions. In the context of monitoring hazardous gases in waste-disposal or processing areas, IoT is used with gas sensors to measure gas concentrations and send data via the internet to the cloud for analysis and notifications. This enables remote monitoring, improving safety, efficiency, and response to hazardous situations. It should be emphasized that careful implementation and sensor maintenance are very important in managing hazardous gases in such environments.

1.2.2. Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is a major greenhouse gas that is formed naturally through the respiration of living things, the burning of fossil fuels, and the decomposition of organic matter. In waste management systems, especially during the composting and decomposition of organic matter, CO_2 gas can be released into the atmosphere through aerobic decomposition [11]. Although CO_2 is naturally present in the atmosphere, its significant increase has caused global warming and climate change. Data from the Intergovernmental Panel on Climate Change (IPCC) shows that CO_2 accounts for more than 75% of global greenhouse gas emissions originating from human activities [6]. In the context of organic waste management, this gas can be produced in large quantities, especially when organic materials degrade in the presence of oxygen [10].

1.2.3. Methane (CH_4)

Methane (CH_4) is the simplest hydrocarbon, a colorless and odorless gas at standard temperature and pressure. This gas is the main component of natural gas and plays a significant role as a greenhouse gas with a global warming potential about 21 times greater than carbon dioxide (CO_2) [1]. Methane is produced through the anaerobic decomposition of organic matter by methanogenic microorganisms in environments such as wetlands, rice fields, and landfills [12]. Research shows that human activities, such as agriculture and waste management, contribute significantly to methane emissions. For example, in the agricultural sector, flooded rice fields create anaerobic conditions that support methane production. [12] found that the application of environmentally friendly technologies can reduce methane emissions in rice fields. Additionally, livestock manure management is also a source of methane emissions, where enteric fermentation in dairy cows produces this gas [9]. Methane gas begins to form approximately 5 to 15 days after organic waste is collected under anaerobic conditions, depending on the composition of the waste, moisture, and ambient temperature. This process is known as methanogenic fermentation, where anaerobic bacteria break down organic matter and produce CH_4 as the final product.

1.3. Research Objective

This study aims to analyze tests whether the gas monitoring system works well when compared to conventional methods at the Wonorejo Compost Center..

2. MATERIALS AND METHODS

This study used an experimental method with a monitoring system design approach. The main hardware used was an ESP32 microcontroller as the control unit, with integrated WiFi [4]. The MQ-4 sensor detects methane gas, while the MQ-135 sensor detects carbon dioxide gas [5]. The system is equipped with a 16×2 LCD as a local display, powered by a stable electronic power supply, in accordance with the basic principles of electronic systems [3]. Measurement data is sent to cloud-based storage via a wireless internet connection, in line with the concept of an IoT-based monitoring system [2]. (Figure 1).

Fig 1. Gas Measuring Device at Wonorejo Compost Center

Data collection was conducted at the Wonorejo Compost Center for two weeks with measurement intervals of every 4 hours. The measurement data is displayed in real time and stored on an online storage platform. To evaluate system performance, a comparison is made with results from laboratory tests using the Gas Chromatography (GC) method.

3. RESULT AND DISCUSSION

3.1. Gas Concentration Measurement Results

Table 1. Gas Concentration Measurement in Clean Air

| Date	Time	CO_2 (ppm)	CH_4 (ppm)
23/6/2025	08:19:00	90.75	0.01
	12:19:00	93.51	0.01
	16:19:00	96.87	0.01
	20:19:00	95.58	0.01
24/6/2025	08:19:00	96.09	0.01
	12:19:00	96.29	0.01
	16:19:00	91.02	0.01
	20:19:00	93.6	0.01

Gas sensor readings were taken to ensure their validity and consistency. The MQ-135 sensor readings showed that the CO2 concentration in clean air ranged from 90 to 97 ppm. The measured CO2 concentration varied significantly. In the initial measurement on June 23, 2025, at 8:19:00 a.m., the CO2 concentration was recorded at 90.75 ppm. After that, the CO2 value ranged from 90.75 to 96.87 ppm (parts per million). This range is lower than the average CO2 concentration in free air. The MQ-4 sensor readings show that the CH4 concentration in clean air is stable at 0.01 ppm. The measured CH4 concentration was very stable at 0.01 ppm in almost all measurements. This value is also much lower than the standard atmospheric methane concentration (approximately 1.9 ppm globally). Overall, this data shows that the device functions and records CO2 values between 90 and 97 ppm, as well as consistently low CH4 values at 0.01 ppm. The following is a graph of the device test results in clean air.
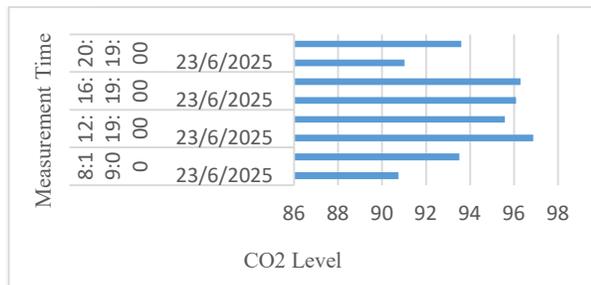
Fig 2. Average Graph of CO_2 Measurements in Clean Air

The graph above shows the results of CO_2 concentration measurements (in ppm) over time. The initial CO_2 concentration was 90.75 ppm at 8:19:00, then reached an equilibrium level of around 90 to 98 ppm at around 12:19:00. From this point until the end of the measurement period, the CO_2 concentration fluctuated within the range of 90-98 ppm. This high stability may indicate that the "clean air" environment where the testing was conducted has a constant CO_2 source (e.g., high background readings of the

device, a closed environment, or the presence of testers) or it can be concluded that the device consistently measures CO_2 at this level and there is no significant sudden drop to 0 ppm, indicating continuous and uninterrupted operation of the instrument throughout the entire testing period. This pattern demonstrates that the instrument provides consistent and reliable readings at the measured CO_2 level under specific test conditions.
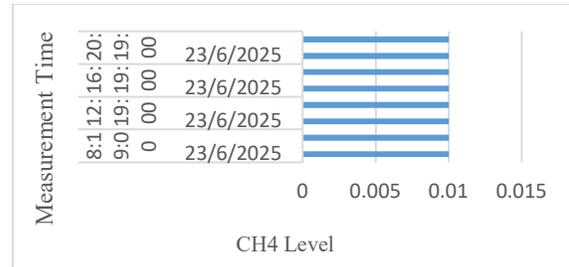
Fig 3. Average Graph of CH_4 Measurements in Clean Air

The graph above shows the results of CH_4 concentration measurements over time. At the start of the measurement (around 8:19:00), the CH_4 concentration was 0.01 ppm, then at the next measurement (around 12:19:00), the CH_4 concentration did not change and remained the same at 0.010 ppm. This was as expected because the device was tested in "clean air," which should have very low pollutant gas concentrations, close to zero. The CH_4 concentration remained stable at 0.010 ppm for the remainder of the test period, until the end of the visible data.

Table 2. Gas Concentration Measurement at Wonorejo Compost Center

Date	Time	CO_2 (ppm)	CH_4 (ppm)
6/25/2025	9:26:00	100.36	0.01
6/25/2025	15:26:00	105.21	0.03
6/25/2025	21:26:00	116.34	0.02
6/26/2025	3:26:00	100.85	0.03
6/26/2025	9:26:00	96.46	0.07
6/26/2025	15:26:00	102.03	0.02
6/26/2025	21:26:00	102.34	0.02
6/27/2025	3:26:00	111.55	0.01
6/27/2025	9:26:00	108.93	0.03
6/27/2025	15:26:00	114.6	0.01
6/27/2025	21:26:00	111.61	0.01
6/28/2025	3:26:00	105.16	0.03
6/28/2025	9:26:00	115.35	0.02
6/28/2025	15:26:00	99.17	0.05
6/28/2025	21:26:00	95.57	0.09
6/29/2025	3:26:00	97.25	0.08
6/29/2025	9:26:00	113.06	0.02
6/29/2025	15:26:00	106.55	0.04
6/29/2025	21:26:00	99.03	0.06
6/30/2025	3:26:00	107.53	0.03
6/30/2025	9:26:00	98.81	0.08

Date	Time		
6/30/2025	15:26:00	112.41	0.02
6/30/2025	21:26:00	106.15	0.03
7/1/2025	3:26:00	104.53	0.04
7/1/2025	9:26:00	102.54	0.04
7/1/2025	15:26:00	110.76	0.02
7/1/2025	21:26:00	104.05	0.03
7/2/2025	3:26:00	97.19	0.08
7/2/2025	9:26:00	97.95	0.08
7/2/2025	15:26:00	119.05	0.02
7/2/2025	21:26:00	117.71	0.02
7/3/2025	3:26:00	112.49	0.02
7/3/2025	9:26:00	101.65	0.03
7/3/2025	15:26:00	119.23	0.01
7/3/2025	21:26:00	114.47	0.02
7/4/2025	3:26:00	112.92	0.02
7/4/2025	9:26:00	106.23	0.03
7/4/2025	15:26:00	101.81	0.03
7/4/2025	21:26:00	97.41	0.07
7/5/2025	3:26:00	117.57	0.02
7/5/2025	9:26:00	106.39	0.03
7/5/2025	15:26:00	100.06	0.03
7/5/2025	21:26:00	102.65	0.03
7/6/2025	3:26:00	109.48	0.03
7/6/2025	9:26:00	99.42	0.05
7/6/2025	15:26:00	116.42	0.02
7/6/2025	21:26:00	113.96	0.02
7/7/2025	3:26:00	112.99	0.02
7/7/2025	9:26:00	105.8	0.03
7/7/2025	15:26:00	110.68	0.02
7/7/2025	21:26:00	109.6	0.02
7/8/2025	3:26:00	111.25	0.02
7/8/2025	9:26:00	97.11	0.07
7/8/2025	15:26:00	105.4	0.03
7/8/2025	21:26:00	96.04	0.09
7/9/2025	3:26:00	107.35	0.03
7/9/2025	9:26:00	103.25	0.03
7/9/2025	15:26:00	98.61	0.05
7/9/2025	21:26:00	97.59	0.05
Average		106.92	0.03

Based on the data above, it shows that the carbon dioxide (CO_2) levels measured at the "Compost House" location varied significantly, recorded in the range of approximately 95.57 ppm to 119.23 ppm during the observation period. Most measurements were above 100 ppm, and daily variations were evident, with (CO_2) levels tending to be higher during early morning (3:26:00), daytime (15:26:00), and nighttime (21:26:00) measurements. the

(CO_2) levels tended to be higher in the early morning (3:26:00), afternoon (3:26:00), and evening (9:26:00) measurements compared to other specific measurements, although the pattern was not always consistent. These fluctuations are normal in a composting environment because CO_2 is the primary product of the decomposition or breakdown of organic matter by microorganisms. Increased biological activity, especially under certain conditions such as changes in temperature, humidity, or aeration, will result in a spike in CO_2 emissions. For example, on July 2, 2025, CO_2 levels peaked at 119.05 ppm at 15:26:00 and 119.23 ppm at 15:26:00 the following day, indicating a possible period of highly active decomposition. Meanwhile, the detected methane (CH_4) levels were significantly lower and more fluctuating, ranging from 0.01 ppm to 0.09 ppm. The majority of (CH_4) measurements were below 0.05 ppm, indicating that the environment in the "Compost House" is most likely aerobic (requiring oxygen), which is optimal for composting. Methane (CH_4) is a very potent greenhouse gas and is usually formed under anaerobic conditions (without oxygen), such as those found in landfills or inside dense compost piles. Although the levels are low, the appearance of (CH_4) levels with values

3.2. Comparison with Laboratory Tests

The results of gas chromatography (GC) analysis of biogas samples tested using a GC7900 model instrument with a TCD (Thermal Conductivity Detector) detector on an HP-PLOT/Q, and operated isothermally at an oven temperature of 43°C. The test results showed three main peaks, namely: a very high peak at a retention time (R.Time) of 0.461 minutes, followed by a small peak at 0.816 minutes, and a fairly large peak at 1.741 minutes. Each peak represents a gas component that has been separated based on its physical properties in the chromatography column. The General Results section summarizes the quantitative data from these peaks, where the Area % column is the key data showing the relative composition in the detected volume. The results indicate that the analyzed gas is dominated by Air at 76.21%. The two main components of biogas identified are Carbon Dioxide (CO_2) at 21.82% (at R.Time 1.741 minutes) and Methane (CH_4) at 1.97% (at R.Time 0.816 minutes). For the standard gas (comparison) containing Methane (CH_4). The instrument used was the GC7900 model, equipped with a Thermal Conductivity Detector (TCD) and an HP-PLOT/Q column, operated at an oven temperature of 43°C for 8 minutes. The purpose of this standard analysis is to determine the specific retention time (R.Time) and response factor (Area/Volume or Area/Concentration) of Methane and Air under the same instrument conditions, thereby enabling accurate quantitative calculations for testing biogas samples. The chromatogram test results show two dominant peaks identified in the standard, namely:

1. Air Peak: Observed at R.Time 0.484 minutes, with an Area% of 29.70634%. Because Air (mainly Nitrogen and Oxygen) is a very light gas, it will pass through the chromatography column the fastest.
2. Methane (CH_4) Peak: Seen at R.Time 0.730 minutes, with a dominant Area% of 70.11355%. This retention time of 0.730 minutes is a very important reference value for identifying methane in actual biogas samples. Additionally, there is a small unknown peak at R.Time 0.185 minutes with a very small Area%

(0.18011%), which may be noise or minor contamination. The standard composition shows a Methane-to-Air ratio of approximately 70% : 30%.

Meanwhile, for standard gas (comparison) containing Carbon Dioxide (CO_2). The instrument used is the GC7900 model with a Thermal Conductivity Detector (TCD) and HP-PLOT/Q column, operated isothermally at an oven temperature of 43°C for 8 minutes. The main purpose of this standard analysis was to determine the specific retention time (R.Time) and response factor for CO_2 under the same instrument conditions, which would later be used as the basis for quantification when testing actual biogas samples. Test results The chromatogram shows two main peaks identified in this standard gas, namely:

1. Air Peak: Appears as a very high and sharp peak at R.Time 0.467 minutes. Quantitatively, Air has an Area% of 36.69803%. Light gases like air (mainly N_2 and O_2) have minimal interaction with the column and therefore exit the fastest.
2. Carbon Dioxide (CO_2) Peak: Appears as a broader and clearer peak at R.Time 1.622 minutes. This peak dominates the Area% at 63.30197%. The retention time of 1,622 minutes is an important reference value because any peak in the biogas sample analysis that appears at this retention time can be definitively identified as CO_2.

In processing the gas monitoring data, it is necessary to convert the units from parts per million (ppm) to volume percent (%). This conversion is important because it allows the measurement data to be compared with reference values or biogas standards expressed in percent. The conversion process is carried out using the following basic formula:

$$Conentration\ \% = \frac{Conentration\ ppm}{10.000}$$

The conversion results show that the average concentration of carbon dioxide (CO_2) gas is 106.92 ppm, which is equivalent to 0.0106%, while the average concentration of methane (CH_4) is 0.03 ppm, equivalent to 0.000003%. These values provide a quantitative picture of the amount of gas detected during the monitoring period. Although the values appear small in percentage form, the results are still significant because they reflect the actual concentration of gas in the air in the context of the biogas monitoring system.
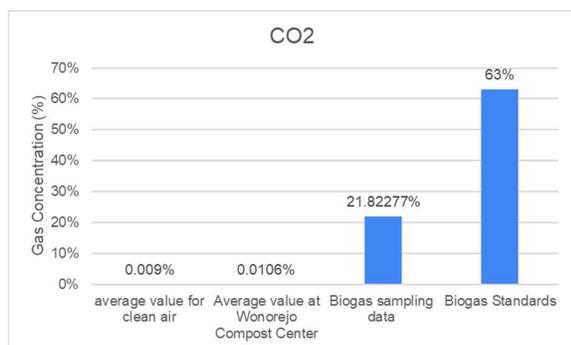

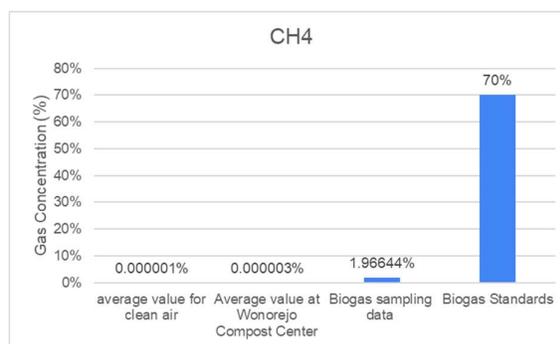**Fig 4.** Comparative Graph of Average CO_2 Measurements

Fig 5. Comparative Graph of Average CH_4 Measurements

Figure 5 shows a comparison of CO_2 and CH_4 gas concentration values from several measurement sources, namely research results in clean air, research results in compost houses, biogas sampling data, and standard biogas composition. The average values of the research results in clean air and the Compost House are very small, 0.010% and 0.0107% respectively, indicating that the CO_2 levels in these environments are low and still within safe limits for ambient air. Meanwhile, the biogas sampling data shows a concentration of 21.82%, and the biogas standard is 63%. When compared to the lab test results, the device measurements are indeed lower. This indicates that the biogas produced from the Compost House sample has a lower CO_2 content than the ideal standard, or it could also indicate limitations in the sensor's accuracy in reading high CO_2 gas concentrations. Overall, this graph shows the prototype device's ability to distinguish CO_2 concentrations under various environmental conditions, while also serving as a basis for evaluating sensor performance and calibration to bring the results closer to the actual biogas standard values.

For comparison of methane gas (CH_4) concentration values obtained from sensor testing under various environmental conditions. In measurements in clean air and the Compost House, the detected CH_4 concentrations were very low, namely 0.000001% and 0.000003%, respectively, indicating that under these conditions, there was almost no significant methane gas in the air. Meanwhile, in the biogas sampling data, the CH_4 concentration value increased to 1.97%. However, when compared to the biogas standard, which has a methane content of around 70%, the measurement results were still much lower. This large difference could be due to several factors, including the quality of the biogas raw materials, fermentation conditions, and the MQ-4 sensor's sensitivity to high CH_4 concentrations. Overall, this graph shows that the prototype device is capable of detecting the presence of methane gas, but it still requires further calibration and optimization so that the readings are closer to the ideal biogas standard value. Laboratory analysis using Gas Chromatography (GC) showed a CO_2 content of 21.82% and a CH_4 content of 1.97% in the biogas sample. The absolute difference between the sensor and GC results is due to the MQ sensor's limitations in detecting high gas concentrations. Nevertheless, the IoT system can consistently represent gas emission patterns and trends.

4. CONCLUSION

Based on the results of the research and discussion, an IoT-based gas monitoring system using ESP32, MQ-4, and MQ-135 sensors was successfully designed and implemented. The system can monitor CH_4 and CO_2 gas concentrations in real time and store data online. The measured gas concentrations in clean air and at the Wonorejo   Compost Center were relatively low, indicating a tendency toward aerobic composting processes. Measurement results show that the average CO_2 and CH_4 concentrations in clean air are 0.010% and 0.000001%, respectively, while in the Compost House, the average concentrations are 0.0107% for CO_2 and 0.000003% for CH_4. Although there are differences in the laboratory test results, the system has consistently displayed gas concentration trends. It is recommended to use sensors with higher accuracy, such as NDIR sensors for CO_2 and TGS sensors for CH_4, to achieve more precise measurements and more valid comparisons with laboratory data.

REFERENCE

[1]   Azmi, M., & Arif, M. (2018). Analisis emisi gas metana sebagai gas rumah kaca dari aktivitas pengelolaan limbah organik. Jurnal Teknik Lingkungan, 14(2), 85–93.

[2]   Chen, Y., Li, X., Wang, H., & Zhang, L. (2021). Internet of Things based environmental monitoring system for hazardous gas detection. Journal of Environmental Informatics,38(1), 45–56.

Enny, S. (2018). Dasar-dasar catu daya pada perangkat elektronik. Yogyakarta: Andi Offset.

[3]   Espressif Systems. (2020). ESP32-DevKitC V4 user guide. Espressif Systems Inc.

[4]   HANWEI ELECTRONICS. (n.d.). MQ-4 gas sensor technical datasheet. Hanwei Electronics Co., Ltd.

[5]   Intergovernmental Panel on Climate Change (IPCC). (2021). Climate change 2021: The physical science basis. Cambridge University Press.

[6]   Kementerian Lingkungan Hidup dan Kehutanan. (2022). Statistik pengelolaan sampah nasional. Jakarta: KLHK Republik Indonesia.

[7]   Kusuma, A. R., & Nugroho, B. S. (2022). Peran rumah kompos dalam pengurangan emisi gas rumah kaca. Jurnal Pengelolaan Lingkungan, 18(1), 44–53.

[8]   Mahmud, A., & Prima, D. (2021). Methane production from livestock manure management systems. Jurnal Teknologi Lingkungan, 22(1), 55–63.

[9]   Probo, M., & Hapsari, R. (2022). Greenhouse gas emissions from organic waste decomposition. Jurnal Pengelolaan Lingkungan, 18(2), 101–110.

[10]   Sutaryo, S., et al. (2020). Carbon dioxide emissions from aerobic composting processes. Jurnal Teknik Lingkungan, 16(1), 25–33.

[11]   Yulianingrum, E., et al. (2019). Methane emission characteristics from anaerobic organic waste treatment. Jurnal Rekayasa Lingkungan, 15(3), 145–153.