https://doi.org/10.1051/e3sconf/202568204002

Distribution analysis of CO_2 gas concentration at the Putri Cempo Landfill Indonesia

Amin Sunarhadi, *Hashfi Hawali Abdul* Matin*, *Daffa Ananda* Risdian, *Devia Rahma* Rizka, *Dinara Afrida* Saleh, *Hanifah Asma* Salsabila, and *Aulia Tsalatsa* Agustina

Departement of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Abstract. This study examines the distribution of carbon dioxide (CO_2) concentrations at the Putri Cempo landfill, Surakarta, which is a significant source of greenhouse gas emissions from organic waste decomposition. Measurements were conducted at eight representative locations, encompassing areas frequently subject to high traffic and landfill activity, areas with minimal activity, and leachate treatment facilities, on two different days (weekdays and weekends) and in two time periods (morning and afternoon). The results indicate that CO_2 concentrations tend to be higher on weekdays and during the day, particularly in areas with high activity intensity, with several locations exceeding the WHO air quality threshold (>1000 ppm). Meteorological factors such as temperature, humidity, and wind speed have been shown to influence CO_2 level fluctuations. Spatial mapping through interpolation reveals uneven emission distribution, with high pollution zones concentrated at the center of landfill activity. These findings emphasize the need for routine monitoring, planting protective vegetation, and time-based emission reduction policies as mitigation strategies to reduce environmental and public health impacts. By identifying critical emission hotspots and key drivers of CO_2 variability, this research provides essential evidence for strengthening local greenhouse-gas mitigation strategies and supporting broader climate change mitigation efforts.

1 Introduction

Most of the house gas glass is methane (CH_4) and carbon dioxide (CO_2), which absorbs heat in the atmosphere and contributes big to global warming and increase temperature. Starting from frequency and intensity incident weather extreme until rise sea level, and its effects on ecosystems and health human, is one of the impact from change climate [1]. The push for reduce greenhouse gas emissions glass, especially carbon dioxide, is a growing problem all over the world, well in a way geographical and in various activities and industries involved. Landfills are a significant source of GHG emissions. Landfills process approximately 1.4 billion metric tons of solid waste annually. The anaerobic degradation of this waste produces large amounts of greenhouse gases (GHG) and methane [2]. According to the

* Corresponding author: hawalihashfi@staff.uns.ac.id

Intergovernmental Panel on Climate Change (IPCC) in a study [3], methane gas is 28 times more powerful than carbon dioxide gas in capturing heat in the atmosphere. Unfortunately, many landfills around the world do not have adequate methane capture facilities. As a result, methane is directly released into the atmosphere from landfills without effective capture and utilization measures [4].

Biomass-rich landfills are also a major source of methane emissions, which further increase the concentration of CO_2 in the atmosphere and accelerate global warming [2,5]. Carbon dioxide (CO_2) gas produced from landfills (TPA) generally comes from biogenic sources and contributes significantly to the greenhouse effect [6]. The more this gas is released into the atmosphere, the temperature will increase and the amount of water vapor in the atmosphere will increase [1]. CO_2 emissions from landfills are influenced by the amount and composition of waste, climate conditions, and the gasification process in waste-to-energy plants [7]. The process of burning waste irregularly and piled up will produce CO_2 due to oxygen being only available on the surface of the waste pile, while the interior lacks oxygen, thus triggering the formation of CO_2 which can be harmful to health.

The Putri Cempo landfill is located in Mojosongo Village, Jebres District, Surakarta City, and has been operating since 1986 as the city's main final disposal site. At the Putri Cempo landfill, several activities are carried out, such as separating waste types, collecting and transporting it, recycling, landfilling, and treating leachate [7]. The landfill area reaches approximately 17 hectares, with the waste management method still dominated by the open dumping system, namely the open accumulation of waste without adequate sanitation processes. Every day, hundreds of tons of waste, especially household waste, are dumped at this location, and the uncontrolled accumulation conditions increase the risk of environmental pollution, such as soil and water pollution due to leachate. The continuously increasing volume of waste at the Putri Cempo landfill has led to the emergence of various types of pollutants, both in liquid, gas, and solid forms. In addition, local topography and wind characteristics also influence the potential for the spread of greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) released from the decomposition of organic material beneath the surface of the waste. Then, the Putri Cempo Fecal Sludge Treatment Plant (IPLT) was built in an area directly adjacent to the landfill, so it is at high risk of heavy metal contamination because it is surrounded by various types of garbage and solid waste [8]. Waste management must involve various parties, including the government, the private sector, and the community, to create an integrated and sustainable system.

In a way theoretical, place disposal end is one of the source anthropogenic main greenhouse gas emissions glass, where carbon dioxide and methane into two components dominant produced from the decomposition process anaerobic and aerobics waste Organic. Open dumping system at landfills such as Putri Cempo not only pollute land and water, but also contributes to greenhouse gas emissions glass from decomposition rubbish organic that is not handled with good [9]. CO_2 can formed during stage beginning degradation aerobics when oxygen Still available, before condition anaerobic dominate and produce methane. Characteristics pile rubbish like humidity, temperature, and type waste influential big to quantity and type of gas formed. One of the approaches processing the middle trash developed is gasification, which is a thermochemical process that converts carbon from waste organic into synthetic gas or syngas, which can be utilized as energy. In addition, the low-level processing and management waste in landfills like Putri Cempo potential make things worse accumulation emission this, which if no monitored and handled, can impact on health public around as well as contribute to change climate globally.

Understanding the distribution of CO_2 concentrations across regions is crucial. High concentrations of carbon dioxide in a region can be an indicator of anthropogenic activities such as fossil fuel combustion and land use changes. Significant increases in CO_2 concentrations pose various threats, both direct and indirect, to the climate system, which can

 https://doi.org/10.1051/e3sconf/202568204002

lead to adverse impacts such as rising sea levels and increasingly extreme weather [10]. Local research also demonstrates the importance of monitoring CO_2 concentrations. A study by [6] in Mojokerto City revealed that most CO_2 is produced by population respiration, followed by LPG use, motor vehicles, and industrial activities. In addition, research by [11] in Gresik Regency showed a significant relationship between increasing CO_2 concentrations and rising local air temperatures.

However, these studies have not examined CO_2 concentration patterns specifically in landfill environments, particularly those utilizing open dumping systems. Therefore, the aim of this study is to analyze and map the spatial distribution of CO_2 concentrations in and around the Putri Cempo Landfill to identify potential emission hotspots and associated environmental risks.

2 Data and methods

2.1 Study area

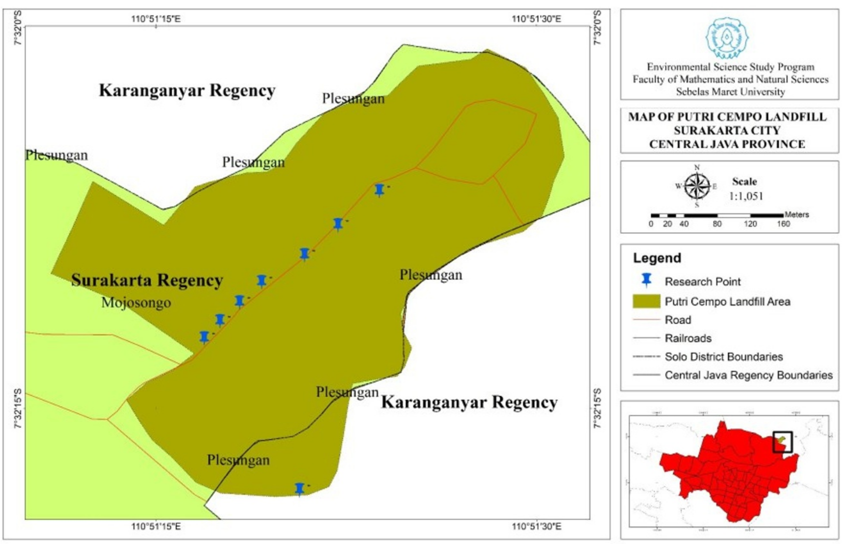

Fig. 1. Research Location

The research location is at the Putri Cempo landfill, which is located in the sub-district Mojosongo, District Jebres, Surakarta City, Central Java. Research point was conducted in the Putri Cempo landfill area and at the location leachate management, which reflects focus studies in the area (Fig. 1.). In this study, observations were conducted at eight different points scattered throughout the landfill area. These points are indicated on the map by blue symbols, and are located from the west to the east of the landfill area. The placement of these points aims to illustrate the diverse environmental conditions surrounding the landfill, particularly in terms of potential impacts on air quality due to activities at the site.

Geographically, the Putri Cempo landfill is located northeast of Surakarta City and directly borders Karanganyar Regency. The landfill is surrounded by several areas, including Mojosongo (which is part of Surakata) and Plesungan (which is part of Karanganyar). Knowing these boundaries is important because the impact of the landfill can be felt not only in Surakarta but also in the Karanganyar area. The map also contains various other important information such as roads, rivers, railways, and city and district boundaries. The landfill area that is the focus of the research is marked in greenish brown on the map. This map uses a scale of 1:1,051, which means it is quite detailed and can help accurately depict the position of the research points. By analyzing eight observation points, this study is expected to provide clear information about the environmental conditions around the Putri Cempo landfill, and assist in better planning and waste management in Surakarta and the surrounding area.

2.2 Sampling technique

The data collection was conducted in real-time over two days—Friday (representing weekdays) and Saturday (representing weekends)—with two observation sessions on each day: morning to midday (09.15–10.55 WIB) and afternoon to evening (13.30–15.25 WIB). Sampling was carried out using a purposive sampling method, based on certain considerations in accordance with the research objectives and referring to SNI 19-7119.6: 2005 concerning Determination of Sampling Locations for Ambient Air Quality Monitoring Tests; measurements were carried out actively for 10 minutes at each of the 8 monitoring points. Sampling was carried out using direct CO_2 gas monitoring research techniques at locations in the Putri Cempo landfill which are estimated to have high CO_2 emission concentrations. The parameters observed included CO_2 concentration using a CO_2 meter as well as meteorological factors such as wind speed, air temperature, humidity, and air pressure using an environmental meter.

2.3 Data analysis

The data obtained was then compared with ambient air quality standards. In this analysis, the quality standards used refer to guidelines from the World Health Organization (WHO), with clean air classified as ranging from 310–330 ppm, while polluted air ranges from 350–700 ppm.

Besides being served in form tables and graphs or diagram, CO_2 gas concentration data is also presented in form map distribution for give visual depiction of distribution spatial CO_2 concentration in the study area. The CO_2 measurement locations that have been equipped with coordinate geographical processed through the interpolation process, with Spline method, to estimate mark concentration at points that are not measurable in a way directly. The results of mapping This displayed in form map thematic that shows variation CO_2 concentration in each zone, so that make things easier in identify the area with level pollution high and supportive analysis more carry on related potential risk environment.

3 Results and Discussions

3.1 Research overview

This study was conducted at the Putri Cempo landfill located in Jebres District, Surakarta City. This site is used as the main location for disposing of domestic waste from Surakarta City and its surrounding areas. Direct field observations indicate that the landfill is used to process and store large amounts of waste. The environment is still open and relatively close to residential areas and wild vegetation. This activity is suspected to influence changes in greenhouse gas levels, such as carbon dioxide (CO_2) in the surrounding air. In this study, data collection was conducted at eight sampling points spread across the landfill area. Each point was selected based on variations in environmental conditions and its distance from the main pollutant source. Measurements were made of four environmental parameters: CO_2 concentration (ppm), air temperature (°C), relative humidity (RH, %), and wind speed (m/s).

These four parameters are interrelated and can provide a general overview of air quality and microclimate conditions around the study site.

The first measurement point in Figure 2 (a) is located at the entrance to the Putri Cempo landfill, which is the main route for operational vehicles such as garbage trucks, pickup trucks, and three-wheeled motorcycles to transport waste. The dense traffic of garbage trucks at this location is a major potential source of CO_2 emissions. Furthermore, this area is also adjacent to the weighing facilities and management office, making it one of the most intensive activity zones around the landfill. One of the points observed in Figure 2 (b) is point 4, which is located on the side of the waste sorting area with visually very dense waste conditions. Direct measurements and documentation were also carried out at this point. Furthermore, the last point, or point 8, is located somewhat further from the center of the landfill, close to a pool of water suspected to be a leachate retention pond. This point is important to observe because the presence of leachate can affect gas emissions and the humidity of the surrounding air (Figure 2 (c)). Overall, the placement of these observation points is designed to represent the overall air conditions around the Putri Cempo landfill, both on weekdays and weekends, and at two different observation times.

Fig. 2. Monitoring Location. (a) Location of point 1—landfill entrance area, (b) Location of point 4 and direct measurements in the field, (c) Location of point 8—leachate reservoir.

3.2 Concentration measurement results

The graph in Figure 3 shows a comparison of CO_2 concentrations (in ppm) between weekdays *and* weekends *at* eight different sampling points. In general, CO_2 concentrations tend to be higher on weekdays than weekends at most points, especially at points 5 and 6, which recorded the highest values, namely 1177.25 ppm and 1119.25 ppm on weekdays. This increase is likely related to high human activity, as well as several vehicles such as motorcycles, pickup trucks, and garbage trucks during weekdays, which contribute to CO_2 emissions. Conversely, on weekends, vehicle activity and operations at the landfill tend to decrease, resulting in relatively lower greenhouse gas emissions, including carbon dioxide (CO_2). Based on WHO guidelines, ambient air quality can be categorized as clean air if the CO_2 concentration is in the range of 310–330 ppm, while air with a concentration between 350–700 ppm is categorized as polluted air. The measurement results show that several points such as points 3, 5, and 6 on weekdays recorded concentrations that exceeded this range. This indicates an increase in CO_2 emissions due to human and vehicle activities around the landfill site, which can impact air quality and the health of workers and the surrounding community if it occurs continuously. In addition, this polluted air can also spread to areas around the landfill, even to residential areas, especially if carried by the wind and environmental conditions are favourable. Therefore, emission control needs to be carried out continuously, for example by routinely monitoring air quality and adding shade plants or trees around the landfill, so that the spread of polluted air can be reduced.

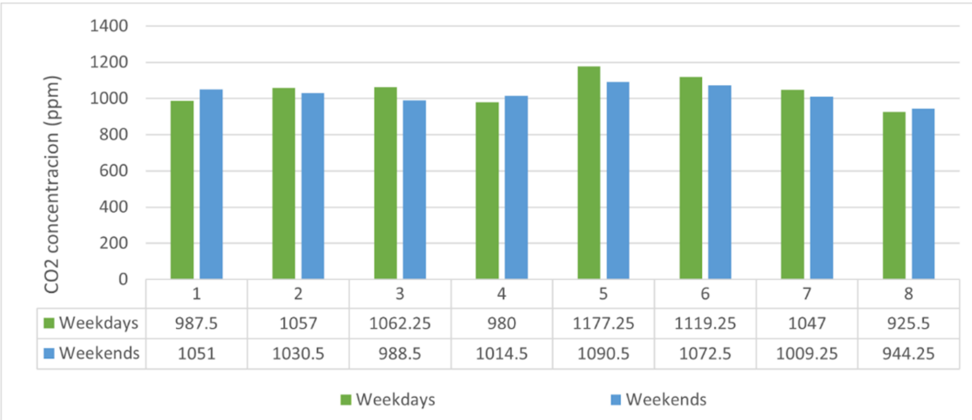

Fig. 3. Graph Comparison average concentration of CO gas on weekdays and weekends.

The graph in Figure 4 shows that the comparison of CO_2 concentrations (in ppm) measured at eight sampling points during two time periods, namely morning (09:00–10:55 WIB) and afternoon (13:30–15:25 WIB), both on weekdays and weekends. In general, it can be observed that CO_2 concentrations tend to be higher during the afternoon compared to the morning, especially on weekdays. For example, points 5 and 6 recorded the highest figures during weekdays at noon, at 1292 ppm and 1214 ppm, respectively. This is related to the increase in human and vehicle activity around the Putri Cempo landfill over time, as well as the influence of weather and sun intensity, which can accelerate the decomposition process of waste, resulting in larger amounts of gases such as CO_2. When compared to the indoor air quality standard set by the WHO (2021), which is 1000 ppm, many points exceed this threshold, especially during weekday afternoons. This indicates that the air quality in the landfill environment is unhealthy and poses a risk to workers and the surrounding community.

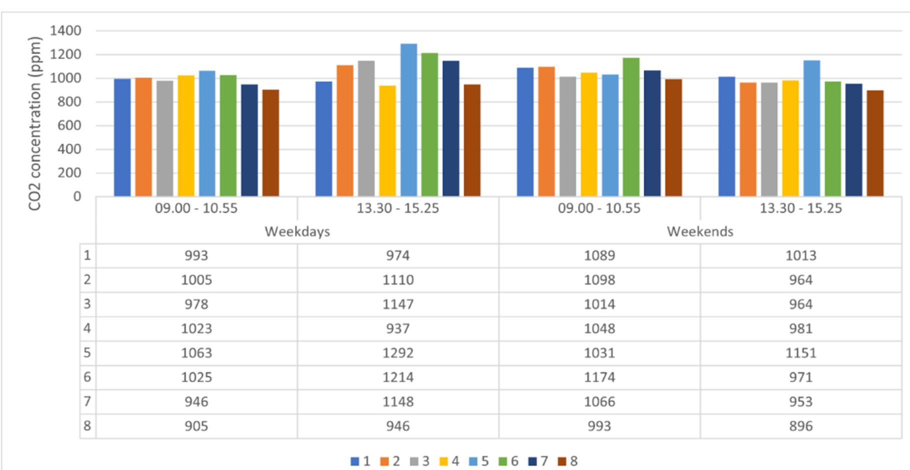

Fig. 4. Comparison graph of average CO gas concentration on weekdays and weekends with morning and afternoon sessions.

3.3 Factors causing high and low CO_2 and meteorological conditions

Atmospheric carbon dioxide (CO_2) levels continue to rise due to various human activities, particularly the burning of fossil fuels, deforestation, cement production, and agricultural and industrial activities. However, the implementation of environmental policies such as carbon taxes and emissions trading mechanisms has been shown to be effective in suppressing emissions. In addition to economic policies and activities, land-use changes, particularly deforestation, also contribute to increased emissions by reducing the biosphere's natural capacity to absorb CO_2. In addition to anthropogenic factors, climatic conditions also significantly influence atmospheric carbon dynamics. In dry years, vegetation experiences severe water stress, resulting in a drastic reduction in its CO_2 absorption capacity, sometimes by as much as 30% or more [12]. Conversely, in wet years, vegetation exhibits increased efficiency in absorbing CO_2, particularly when high rainfall is combined with high atmospheric CO_2 concentrations. Therefore, seasonal climate variability and environmental policies have an important role in regulating the global carbon balance, so that emission mitigation efforts must consider both socio-economic aspects and ecosystem responses to climate change.

The high CO_2 levels at the Putri Cempo Landfill are not only due to global factors such as the economy or government policies, but are also greatly influenced by daily activities in the field, weather such as wind, rain, and temperature, as well as natural processes within the waste piles. At the Putri Cempo Landfill, the fluctuations in CO_2 gas levels are apparently greatly influenced by daily activities and weather conditions around the site. From observations made, CO_2 levels tend to be high when the weather is hot, there is no wind, and many heavy equipment and garbage trucks are in operation. These heavy equipment and vehicles emit CO_2 gas from fuel combustion has a negative impact on the environment due to increased emissions of this gas. The conditions at the Putri Cempo Landfill are exacerbated by the lack of wind to help disperse this gas, ultimately CO_2 gas accumulates around the ground surface. Conversely, when it rains, the weather is cloudy, or the wind blows quite strongly, CO_2 levels usually decrease. Wind helps disperse the accumulated gas, while rain can help bind CO_2 and carry it to the ground through a natural process called wet deposition [13]. Air temperature also plays a role in determining CO_2 levels. As air temperatures rise, the decomposition of organic waste in landfills accelerates. This causes more CO_2 and methane (CH_4) to be released into the air. This is why emissions of these gases are often higher during the day, especially in active areas of landfills.

Table 1. Condition measurement results meteorology

Sampling Points	Time (WIB)	Weekdays			Weekends		
		Temp (°C)	RH (%)	WS (m/s)	Temp (°C)	RH (%)	WS (m/s)
1	09.00-09.10	32.7	59.60	0.9	34.0	53.35	1.3
	13.30-13.40	31.1	59.40	0.6	32.9	58.55	1.0
2	09.15-09.25	33.8	54.05	1.0	36.4	58.30	0.8
	13.45-13.55	27.7	73.20	0.5	36.5	46.75	1.2
3	09.30-09.40	34.4	58.40	0.8	34.7	56.90	0.8
	14.00-14.10	26.1	72.05	0.7	35.1	56.20	1.1
4	09.45-09.55	36.9	45.45	0.7	32.4	58.85	0.8
	14.15-14.25	25.8	74.35	0.9	35.2	50.85	0.5
5	10.00-10.10	35.0	57.25	1.1	32.7	58.85	0.8
	14.30-14.40	26.6	76.75	0.6	34.1	54.05	0.7
6	10.15-10.25	31.3	57.80	1.3	31.6	55.90	0.9
	14.45-14.55	27.1	75.55	1.3	34.6	56.00	0.8
7	10.30-10.40	33.3	59.30	1.1	31.6	59.60	0.6
	15.00-15.10	26.7	78.75	0.9	33.2	57.35	1.0
8	10.45-10.55	34.2	58.05	1.7	30.9	52.15	0.8
	15.15-15.25	26.0	77.80	1.4	35.2	57.35	0.9
AVERAGE		**30.54**	**64.86**	**0.94**	**33.82**	**55.69**	**0.84**

Based on the data in Table 1, weather conditions at the Putri Cempo landfill show that on weekday mornings, the weather is hot with fairly high temperatures, ranging from 32 to 36.9°C. Humidity is still low to moderate, ranging from 45.45% to 59.6%. Wind speed is also low, ranging from 0.6 to 1.3 m/s. However, as the day progresses into the afternoon, the air temperature drops significantly, even as low as 25.8°C. Conversely, humidity rises sharply, reaching as high as 78.75%. This change indicates the presence of light rain or drizzle in the area. Since wind speeds remain low, the rain is likely to be localized, without strong winds, and only occur in certain areas. This drop in temperature occurs naturally due to the rain. Rainwater absorbs heat from the surrounding air, causing the air to become cooler. In addition, when it rains, the amount of water vapor in the air also increases, causing the humidity (RH) to rise. Meanwhile, on weekends, mornings also show hot weather. The highest temperature reaches 36.5°C, with low humidity (around 46.75–59.6%) and not too strong winds. However, unlike weekdays, there are no signs of rain from noon to late afternoon on weekends. The temperature has dropped slightly, ranging from 30.9–35.2°C, and humidity has increased slightly, but not as high as during rain. This is due to light cloudy weather, but no rain. Additionally, wind speed has increased slightly during this time, reaching up to 1.4 m/s at some locations. This wind helps make the air feel cooler and disperses the clouds. Therefore, even though it is not raining, the weather on weekends from noon to evening feels somewhat cloudy and windy. Overall, weekdays feel cooler and more humid from noon to evening due to local rain. Meanwhile, weekends remain hot, but the blowing wind and clouds covering the sun make the weather not too intense.

3.4 CO_2 gas distribution pattern

Landfills are considered a major source of greenhouse gases, especially methane (CH_4) and carbon dioxide (CO_2), as global warming is one of the major environmental crises. In recent decades, various approaches have been developed to assess surface LFG emissions, including direct field measurements and estimation techniques based on landfill characteristics and waste degradation processes. There are five sources of emissions from landfills: landfill leachate emissions, emissions associated with fresh waste disposal also referred to as “fresh waste emissions” and emissions from the surface of temporarily or permanently closed landfills.

In this study, sampling points were taken in open areas, closed areas, and leachate disposal sites. The sampling points were taken at areas with high activity, which are indicated to cause pollution. At points 1, 2, 3, and 4, sampling was carried out in open areas, areas that are often used as traffic points for garbage transport vehicles and waste management activities in the Putri Cempo garbage mountain area. These results are in accordance with research conducted by [14] after the peak, there was a decrease in CO_2 gas emissions. This shows that CO_2 gas emissions depend on the quantity of waste and the level of biodegradation. The amount of CO_2 production will decrease because the amount of waste that will decompose decreases every year, and the type of solid waste that will decompose can also affect the amount of CO_2 production. At points 5, 6, and 7 are areas used for waste management, although outside vehicle mobility or activity is not as high as at points 1 to 4. Waste collectors who collect and deliver municipal waste to the final disposal site and processing site by trucks, whose pollutant emissions cannot be ignored. Area 3, point 8, at the leachate disposal site, which is a potential source of gas emissions due to the anaerobic decomposition process. Leachate is wastewater that collects due to rainwater percolation at the final disposal site.

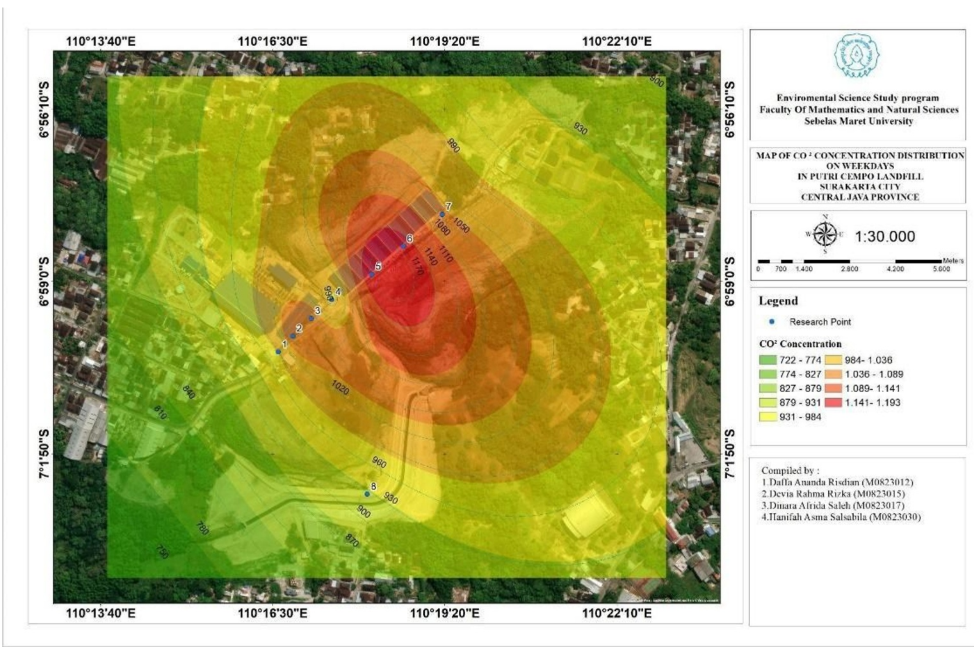

Fig. 5. Map of CO_2 Concentration Distribution on Weekdays in Putri Cempo Landfill.

https://doi.org/10.1051/e3sconf/202568204002

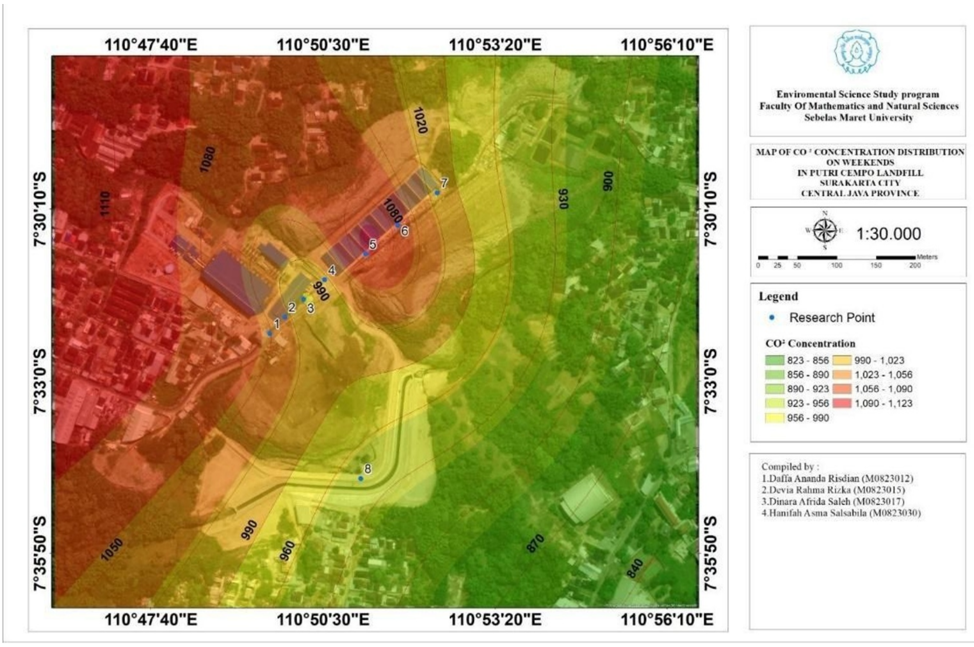

Fig. 6. Map of CO_2 Concentration Distribution on Weekend in Putri Cempo Landfill.

Based on the distribution map of CO_2 concentrations at the Putri Cempo Landfill on weekdays and weekends, there are significant differences in the distribution pattern and intensity of CO_2 concentrations at the study site. On the weekday map (Figure 5), the highest CO_2 concentrations are in the range of 1,141–1,193 ppm, which are distributed predominantly in the central area near points of high activity. The red zone representing the highest emissions expands significantly, indicating that activity on weekdays tends to be more intense and produces greater emissions. Conversely, on weekends, CO_2 concentrations are relatively lower and more limited in distribution, with the highest value reaching around 1,123 ppm (Figure 6). Green and yellow colours dominate most areas, indicating that carbon monoxide emissions tend to decrease, likely due to reduced operational activity at the landfill. This indicates a decrease in operational activity on weekends, which has an impact on decreasing CO_2 emissions. This difference reinforces the indication that CO_2 concentrations are significantly influenced by the intensity of human activity, particularly vehicles, active waste management, and microclimate conditions around open areas and leachate. The selected sampling points provide a spatial representation of actual field conditions relative to the main sources of emissions.

3.5 Recommended strategy and policy

Based on research results at the Putri Cempo landfill site, which showed CO_2 concentrations exceeding ambient air quality standards according to the WHO. High CO_2 concentrations were particularly evident during operational activities on weekdays and during the daytime. the recommended control strategy is to conduct regular air quality monitoring and increase protective vegetation around the landfill area to enhance carbon absorption, as supported by research [15], revealing that vegetation growing on landfill cover can absorb greenhouse gases such as CO_2 and improve the efficiency of biocovers in reducing emissions. Additionally, optimizing the landfill's operational schedule during peak emission hours is necessary because CO_2 emissions are significantly influenced by the intensity of activities and the volume of waste processed. In areas with high leachate emission potential, such as point 8, the implementation of leachate treatment systems and strict emission monitoring is crucial, in line with research highlighting leachate as the primary source of greenhouse gas emissions. From a policy perspective, regulating the operational hours of landfills and restricting vehicle activities during peak emission hours can be incorporated into stricter local regulations. In addition, the implementation of landfill gas recovery technology and the utilization of clean energy should be encouraged through incentives or other supportive policies, as shown by that policy instruments such as carbon taxes and clean energy subsidies have proven effective in significantly reducing CO_2 emissions.

4 Conclusion

This study successfully achieved its objective of analyzing the spatial and temporal distribution patterns of carbon dioxide (CO_2) at the Putri Cempo Landfill, Surakarta. The results show clear variations in CO_2 concentrations driven by operational intensity, observation time, and meteorological conditions. CO_2 levels consistently rise during weekdays and in the afternoon, especially in areas with high vehicle movement and active waste processing. Spatial mapping confirms the concentration of elevated CO_2 in the central activity zones, highlighting localized hotspots of greenhouse gas emissions. Overall, the measured CO_2 concentrations exceeded WHO clean air thresholds, indicating degraded air quality that poses risks to both workers and surrounding communities. These high emissions are influenced by waste transport activities, heavy equipment operation, organic waste decomposition, and weather factors such as temperature, humidity, and wind patterns. The findings emphasize that unmanaged landfill operations contribute not only to local air pollution but also to broader climate change challenges through the continuous release of greenhouse gases. Therefore, strengthening emission mitigation efforts—such as routine air quality monitoring, expanding vegetative buffers, improving waste handling schedules, and implementing stricter operational regulations—is essential. Prioritizing sustainable landfill management policies will be critical to reducing community exposure and supporting regional climate resilience.

Acknowledgment

Authors acknowledge special thanks to Universitas Sebelas Maret for the Research Group Grant Programme, Grant Number: 371/UN27.22/PT.01.03/2025, which has supported for this study.

References

1. M. Filonchyk, M. P. Peterson, L. Zhang, V. Hurynovich, and Y. He, Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Science of The Total Environment. **935**, (2024). https://doi.org/10.1016/j.scitotenv.2024.173359
2. S. Syafrudin, W. D. Nugraha, H. H. A. Matin, E. S. Saputri, and B. Budiyono, The Effectiveness of Biogas Method from Rice Husks Waste: Liquid Anaerobic Digestion and Solid-State Anaerobic Digestion. IOP Conference Series: Earth and Environmental Science. **448**, 1 (2020). https://doi.org/10.1088/1755-1315/448/1/012007
3. R. O. P. Prianto and R. H. A. Murti, Estimasi Timbulan Emisi Gas Metana dari Kegiatan Penimbunan Sampah di TPA Desa Selopuro Kabupaten Ngawi dengan Metode IPCC 2006. Jurnal Serambi Engineering. **9**, 3 SE-Articles (2024)

4. R. Li, B. Xi, X. Wang, Y. Li, Y. Yuan, and W. Tan, Anaerobic oxidation of methane in landfill and adjacent groundwater environments: Occurrence, mechanisms, and potential applications. Water Research. **255**, (2024). https://doi.org/10.1016/j.watres.2024.121498
5. D. V. Pheakdey, V. Noudeng, and T. D. Xuan, Landfill Biogas Recovery and Its Contribution to Greenhouse Gas Mitigation. Energies. **16**, 12 (2023). https://doi.org/10.3390/en16124689
6. R. Faradina, T. A. S. Haji, and B. Suharto, Agihan Polutan CO 2 Di Kota Mojokerto Dengan Sistem Informasi Geografi (SIG) The Spread of Carbondioxide Gases Using Geographic Information System in Mojokerto City. Jurnal Sumberdaya Alam Dan Lingkungan. **2**, 2 (2015)
7. L. Brilli, P. Toscano, F. Carotenuto, S. Di Lonardo, P. Di Tommasi, V. Magliulo, A. Manco, L. Vitale, A. Zaldei, and B. Gioli, Long-term investigation of methane and carbon dioxide emissions in two Italian landfills. Heliyon. **10**, 8 (2024). https://doi.org/10.1016/j.heliyon.2024.e29356
8. A. Sunarhadi, L. Kusumaningrum, D. A. Nirwasita Hartono, D. A. Naafi, M. T. Sutrisno, U. Mahmudah, and M. A. Alzahabi, Accumulation of Copper (Cu) and Cadmium (Cd) Ions in Settling Basins to Assess the Effectiveness of the IPLT TPA Putri Cempo, Surakarta. IOP Conference Series: Earth and Environmental Science. **1414**, 1 (2024). https://doi.org/10.1088/1755-1315/1414/1/012032
9. A. Ghaida Fathassabilla and W. Budianta, PENCEMARAN TANAH OLEH Pb DAN Cd DI SEKITAR TEMPAT PEMBUANGAN AKHIR (TPA) PUTRI CEMPO, KOTA SURAKARTA. KURVATEK. **8**, 1 (2023). https://doi.org/10.33579/krvtk.v8i1.3919
10. Y. Hou, W. Liu, L. Wang, F. Wang, J. Zhu, and S. Wang, Characterizing the Regional Differences in Carbon Dioxide Concentration Based on Satellite Observations in the Beijing-Tianjin-Hebei Region during 2015–2021. Atmosphere. **15**, 7 (2024). https://doi.org/10.3390/atmos15070816
11. Moh. Zulfan Maulidan Wahyu Andriansyah and Siti Zainab, Analisis Korelasi dan Pemetaan Konsentrasi Karbon Dioksida (CO2) Terhadap Suhu Udara di Kabupaten Gresik. Reslaj: Religion Education Social Laa Roiba Journal. **6**, 12 (2024). https://doi.org/10.47467/reslaj.v6i12.4777
12. A. M. van der Woude, W. Peters, E. Joetzjer, S. Lafont, G. Koren, P. Ciais, M. Ramonet, Y. Xu, A. Bastos, S. Botía, S. Sitch, R. de Kok, T. Kneuer, D. Kubistin, A. Jacotot, B. Loubet, P.-H. Herig-Coimbra, D. Loustau, and I. T. Luijkx, Temperature extremes of 2022 reduced carbon uptake by forests in Europe. Nature Communications. **14**, 1 (2023). https://doi.org/10.1038/s41467-023-41851-0
13. Y. Yuan, Q. Li, J. Deng, X. Ma, X. Liao, J. Zou, J. Liao, H. Huang, and H. Dai, Response mechanism of soil leachate and disinfection by-product formation to extreme precipitation events under continuous drought scenario. Science of The Total Environment. **916**, (2024). https://doi.org/10.1016/j.scitotenv.2024.170123
14. C. Ramprasad, H. C. Teja, V. Gowtham, and V. Vikas, Quantification of landfill gas emissions and energy production potential in Tirupati Municipal solid waste disposal site by LandGEM mathematical model. MethodsX. **9**, (2022). https://doi.org/10.1016/j.mex.2022.101869
15. D. S. Attalage, J. P. A. Hettiaratchi, A. Chu, D. Pokhrel, and P. A. Jayasinghe, Impact of Landfill Gas Exposure on Vegetation in Engineered Landfill Biocover Systems Implemented to Minimize Fugitive Methane Emissions from Landfills. International

Journal of Environmental Research and Public Health. **20**, 5 (2023). https://doi.org/10.3390/ijerph20054448