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Greenhouse Gas Emission Inventory at Benowo Landfill Using IPCC Method

Muhammad Ilham Muzakki[1*], Raden Kokoh Haryo Putro[1]

[1]Environmental Engineering Study Program, Faculty of Engineering and Science, UPN "Veteran" East Java, Surabaya

* **Email correspondence**: 20034010075@student.upnjatim.ac.id

Abstract
Potentially contribute 296 MTon CO_2 eq (10.32%) of total greenhouse gas (GHG) emissions by 2030, with an annual growth projection of 6.3% using the Business as Usual (BAU) projection from 2010 to 2030. Approximately seventy percent of all waste is organic, making household waste one of the primary sources of urban waste. This study was conducted at the Benowo Landfill in Surabaya City. The SNI 19-3964-1994 method was used to sample the waste composition and generation at the landfill. Waste generation projections considering population growth were made up to 2030. This study compares methane gas emissions from three scenarios: scenario 1, waste is directly landfilled; scenario 2, waste is reduced through composting and 3R processing; and scenario 3, waste is processed at the landfill through gasification. Inventory calculations using the 2006 IPCC guidelines show that the highest greenhouse gas emissions (CO_2 and CH_4) come from the landfilling scenario, with the most significant CH_4 emissions and the most minuscule CO_2 emissions. The gasification scenario produces the most essential CO_2 and minuscule CH_4 emissions due to using aerobic systems and combustion.

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1. Introduction
According to Presidential Decree No. 98 of 2021, (GHG) emissions are gases found in the atmosphere, both from natural processes and anthropogenic activities that emit and absorb infrared light (den Elzen et al., 2016). Naturally, greenhouse gas emissions are formed from several natural phenomena such as volcanic eruptions, decomposition processes by microorganisms and evaporation of seawater by solar heat. However, greenhouse gas production has also increased drastically due to human activities. Increased production of (GHG) results in changes in the atmosphere's composition, causing global warming. The greenhouse gases that have the highest concentrations in the atmosphere are carbon dioxide (CO_2), methane (CH_4), and nitrogen (N_2O) (Nord & Bolland, 2020).
Based on the Nationally Determined Contribution (NDC) document, Indonesia in 2010 produced 1,334 MTon CO_2 eq of greenhouse gas emissions. In 2010, land conversion operations and forest and land fires contributed 48.5% of Indonesia's total GHG (greenhouse gas) emissions, making it the primary source of emissions with 88 MTon CO_2 eq (6.59%) of total (GHG) emissions in Indonesia in 2010, waste production was ranked fourth (Ade, 2019). Although the level of (GHG) emissions from the waste sector is not as significant as other sectors, such as forest fires (48.50%) and energy (33.97%), the waste sector has excellent potential to continue producing (GHG) emissions in the future. The waste industry has the

potential to contribute (GHG) emissions of 296 MTon CO_2 eq (10.32%) of total (GHG) emissions in the 2030 decade with an annual growth projection of 6.3% using the Business as Usual (BAU) projection from 2010 to 2030.
There is a linear relationship between potential emissions (GHG) and increased waste production. Around seventy percent of all waste is organic, making household waste one of the primary sources of urban waste (Nudin, 2020). Only 60%-70% of Indonesia's total urban waste is estimated to be served by waste management companies that are allowed by the government to be transported to landfills.

2. Methodology

Overview of the Study Area

This research was conducted at the Benowo Final Processing Site (TPA) in Sumber Rejo Village, Pakal District, Surabaya City. The status of the Benowo TPA is under the auspices of the city government and is managed by PT. Sumber Organik. The Department of Cleanliness and Green Open Space of the City Government stated that waste production in Surabaya City has increased to around 9896.78 m^3/day, with the Benowo TPA processing an average of 1628 tons/day of waste (Azizah, 2024; Mahira & Karjoko, 2024).

Study of Waste Production and Composition at Benowo Landfill

The waste generation data at the Benowo TPA obtained is the weight data of waste entering the Benowo TPA. The total mass of clean waste for each truck when passing through the weighing device is the weight of the waste (*Weight Volume Analysis)*. Waste generation data collection was carried out for 8 days. This is following the waste composition data collection schedule.
The waste composition was directly sampled with the SNI 19-3964-1994 technique for eight days at the Benowo TPA. The waste taken that had just arrived and was unloaded by a garbage truck (Agency, 2002; Meena et al., 2023). A total of 100 kg of waste was taken and put into *a density box* measuring 0.5 mx 0.5 mx 1 m, which was then calculated to obtain density data from the waste (Yulianto, Firdausy, Riduan, & Mahyudin, 2023). The waste was obtained using the recommended *load-count* and *mass-volume analysis methods,* which were modified to be applied according to field conditions. The composition sampling procedure applied is as follows.

1. The unloading area for garbage trucks is determined.
2. The determination of the load is estimated at 10% of the waste collected in the unloading area of the garbage truckload. The waste is taken 100 kg in the previously mixed part.
3. Separate all the compositions of mixed waste based on the composition that has been determined into the selected composition.
4. Calculate the weight of each waste composition and record it.

Population Projection of Surabaya City

This study estimates the population of Surabaya City until 2030. This 2030 projection is calculated by considering the population projection of Surabaya City as supporting data. Using the least squares, arithmetic, and geometry methodology, the population projection of Surabaya City is selected as the best approach based on *the correlation factor* (r) and standard deviation value (s) (Azwar, Irawan, & Naufal, 2021).

1. Arithmetic Method

   Population projection using the arithmetic method assumes that population growth will continue to increase constantly in the following year. However, long-term projections may be less accurate if there are significant changes in the factors that influence population growth. So, the following formula is obtained:

$$P_n = P_0 + Ka\,(T_n - T_0)$$

$$\text{with, Ka} = \frac{T2 - T1}{P0 - P1}$$

Information:
P_n: Estimated total population in the nth year
P_0: Total population in the base year
P_1: Population in year 1
P_2: Total population in the last year
Ka: Rate of change in population per year
T_n: Desired year for population projection
T_0: Base year for projection calculations

2. Geometry Method
   This Geometric Method is based on the concept that total population growth will increase consistently and continuously without considering possible decreases or fluctuations in population numbers.

$$P_n = P_0 (1 + r)^n$$

   Information:
   P_n: Estimated total population in the nth year
   P_0: Total population in the base year
   r: Population growth rate per year
   n: Total interval years
3. *Least Square* Method
   The least square method determines the similarity between the population (Y) and the year (X) obtained from the straight line and *trendline* of the existing data. The following is the calculation formula for the Least Square method:

$$Y = a + bx$$

$$\text{with, a} = \frac{(\Sigma Y)(\Sigma X^2) - (\Sigma X)(\Sigma XY)}{(\Sigma X^2) - (\Sigma X)^2}$$

$$b = \frac{n(\Sigma XY) - (\Sigma X)(\Sigma Y)}{n(\Sigma X^2) - (\Sigma X)^2}$$

   Information:
   Y: Regression line variable value
   X: *Independent variable* (free)
   a: Constant
   n: Number of data

Surabaya City Waste Generation Projection

Once the population estimate of Surabaya City in 2030 is available, the average waste generation (Kg/person/day) can be used to project the waste generation at the Benowo TPA, according to SNI 19-2454-2002. The calculation formula for the projection of waste generation at the Benowo TPA in 2030 is as follows (Nudin, 2020).

$$M\,t = Fp \times T \times Pt \times 365$$

Information:
Mt: Amount of waste generated in year t (kg)
Fp: Service factor (%)
T: Average waste production (kg/person.day) or (m^3 / \person.day)
Pt: Projection of total population in year t

Selection of CO_2 and CH_4 Gas Emission Generation Scenarios

The basis for selecting scenarios for waste management in Surabaya is as follows.

1. Scenario 1 means that since the waste entered the landfill, the waste has piled up. In this scenario, methane gas emissions are calculated by assuming that the waste is transported from the source and then enters the Benowo TPA 100% directly buried without going through a composting or recycling process at the source.
2. Scenario 2 means waste that has been reduced by using the composting method at the source. This process helps reduce the amount of waste produced and disposed of in landfills. Scenario 2 in this calculation is seen from the reduction process using the composting method and 3R containing food, garden and paper waste before going through the transportation process to the Benowo Landfill. The amount of waste reduction brought to the Benowo Landfill is assumed that the composting reduction is 34.34% and 3R is 13.59% at the TPS3R in Surabaya City.
3. Scenario 3 means that waste entering the landfill is utilized as an electricity generator with gasification processing technology. It is estimated that by using gasification technology, emissions from converting waste into energy can be significantly reduced, reducing the negative environmental impact. In this scenario, the amount of waste to be gasified is 56% of the total waste generated entering the landfill, and the remainder is dumped or in the landfill, which is 44%.

House Gas Emission Calculation Formula

The technique chosen in this study uses the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Tier II) (Change, 2013; CHANGE, 2007).

1. CH_4 emissions in the *landfilling process*

   $$DDOC_m \text{ deposited} = MSW \times DOC \times DOC_f \times MCF \quad (1)$$

   $$L_0 = DDOCm \text{ deposited} \times F \times \frac{16}{12} \quad (2)$$

   $$CH_4 \text{ gas emissions in year } t = (CH_4 \text{ generated} - Rt) \times (1 - OX) \quad (3)$$

   Information:
   $DDOC_m$: Total mass that can be decomposed (tons or Gg)
   MSW: Amount of waste generated based on composition (tons)
   DOC: Biodegradable organic carbon (Default 15%)
   DOC_f: Fraction of decomposed DOC (Default 0.5)
   MCF: CH_4 correction factor aerobic decomposition (Default 0.5)
   Σ CH_4 generated: A particular example of organic damage stored in waste can produce CH4 $_{in}$ less than a year (DDOC).
   L_0: CH_4 gas formed
   F: Fraction of CH4 $_{in}$ landfill (Default 0.5)
   Rt: Recovery CH_4 at TPA
   OX: Oxidation factor (Default 0.1)
2. CH_4 emissions in the *composting process*

   CH_4 emissions = Σ (M *i* x E *fi*) x 10^{-3} – R

   Information:
   Mi: Total mass of composted waste (Gg/year)
   Efi: Emission factor in the composting process ($g.CH_4/Kg$)
   R: Total recovery of CH_4 emissions ($Gg.CH_4$) (Default 0)
3. Emissions in the gasification process

   Emissions are generally considered insignificant because the combustion conditions in gasification, such as high temperatures and long residence times, ensure complete combustion. As a result, the main emission from waste incineration is CO_2. The calculation formula for gasification is as follows:

$$CO_2 \text{ emissions in year } t = IW_t \times CCW \times FCF \times EF \times \frac{44}{12}$$

Information:
IWt: Amount of waste burned
CCW: Fraction of carbon content in waste (Default 40%)
FCF: Fossil carbon fraction in waste (Default 40%)
EF: Combustion efficiency
44/12: Conversion of C into CO_2

In this study, the technique of sampling the composition and production of waste at the Benowo TPA was carried out using the SNI 19-3964-1994 method for eight days, with a load-count and mass-volume analysis approach that has been modified to suit field conditions. The main parameters in calculating greenhouse gas emissions include waste production and composition, organic carbon decomposition factors, and oxidation corrections and methane recovery. The IPCC 2006 Tier II method was chosen because it provides more accurate estimates than Tier I by considering the specific characteristics of waste and local environmental factors. The assumptions used in the calculation include default values from the IPCC such as decomposable carbon fraction (DOC), methane recovery efficiency (Rt), and decomposition correction factor (MCF), with some adjustments based on empirical data from the study location. This approach allows for more representative calculations of the waste management scenarios compared in the study, including conventional landfills, reduction through composting and 3R, and processing with gasification technology.

3. Result & Discussion

Waste Composition and Generation

The weight of waste entering the Benowo TPA is used to obtain the amount of waste production at the TPA. Waste production data collection was carried out for 8 days. The weight of waste on the garbage truck scale and composition are as follows.

Table 1. Percentage of Waste Composition

Waste Composition	Day to (Kg)							
	1	2	3	4	5	6	7	8
Food Waste	6.25	22.85	14.08	21.80	21.20	22.22	21.69	15.66
Garden	7.95	16.55	11.42	12.80	23.90	26.08	15.71	11.34
Wood and Straw	19.60	8.20	14.50	14.50	7.50	7.50	17.60	10.25
Paper	7.50	7.60	6.60	6.60	8.20	8.20	5.00	6.40
Textile	7.25	3.31	4.34	3.35	7.18	11.96	2.95	2.80
Disposal of Napies	12.35	5.39	8.06	9.05	11.22	6.44	6.65	11.53
Rubber and Leather	6.20	4.30	3.60	6.00	1.60	1.60	2.40	1.00
Plastic	28.60	21.40	26.20	17.40	12.00	12.00	17.80	32.33
Metal	0.50	0.60	0.70	0.50	0.60	0.60	0.80	1.60
Glass	1.40	4.20	6.30	4.00	3.20	1.40	5.00	4.80
Residue	2.40	5.60	4.20	4.00	3.40	2.00	4.40	2.29
Total	100	100	100	100	100	100	100	100
Total Percentage	**18%**	**16%**	**12%**	**7%**	**5%**	**9%**	**3%**	**21%**

Waste generation can be determined by considering population growth as well. This initializes the population projection calculation, which produces an average standard deviation value and correlation factor. So, from the calculation of 3 population projection methods, the least square method has a correlation factor close to 1.

Table 2. Suitability Test

Perbandingan Korelasi (r)	
Aritmatika	0,4139
Geometri	0,2620
Least Square	0,4139

To estimate waste generation based on population, information was collected on the waste that has passed through the Benowo TPA over the past five years and projections until 2030. The results of the projection of the amount of waste entering the Benowo TPA are as follows, using the least squares method.

Table 3. Projection of Waste Generation and Population

Year	Population (people)	Generation (tons/year)	Generation (kg/year)
2020	2874314	577414	577414370
2021	2880284	578958	578958210
2022	2987263	580502	580502050
2023	3009286	582046	582045890
2024	3028545	597863	597863057
2025	3043841	600883	600882621
2026	3059137	603902	603902184
2027	3074433	606922	606921747
2028	3089729	609941	609941311
2029	3105025	612961	612960874
2030	3120321	615980	615980438

The results of the calculation of waste generation projections based on the number of residents show that the average generation for the population of Surabaya City is 0.57 kg/person/day. This follows the provisions of SNI 19-2454-2002, which state that waste generation based on the size of a city is 0.4 - 0.5 Kg/Person/day (Ramandei & Nawip, 2022).

Emission Calculation Scenario 1

Using scenario 1, methane gas production is calculated, if waste reaches the Benowo landfill and is piled up without further processing considerations. The following is an example of calculating methane release for organic waste (food waste) in 2020.

DDOC $_m$ deposited (food *waste)* = MSW x DOC x DOCf x MCF
= 108919.05 Tons x 0.21 x 0.5 x 0.5
= 5522.67 Tons or Gigagrams

CH_4 gas formed (food *waste)* = DDOCm deposited x F x 16/12
= 5522.67 Tons x (0.5) x 16/12
= 3672.57 Tons or Gigagrams

CH_4 gas emissions in 2024 (Accumulation of all compositions) = (CH_4 generated − Rt) x (1 − OX)
= (11853.26 Tons – 0) x (1 – 0.1)
= 10667.93 Tons or Gigagrams

Table 4. Results of Calculation of Accumulated CH_4 and CO_2 Emissions

Year	Accumulated Emissions	
	Methane (CH_4)	***Carbon Dioxide (CO_2)***
2020	10667.93	26669.83
2021	10696.46	26741.14
2022	10724.98	26812.45
2023	10753.50	26883.75
2024	11045.73	27614.32
2025	11101.52	27753.79
2026	11157.30	27893.26
2027	11213.09	28032.73
2028	11268.88	28172.20
2029	11324.67	28311.67
2030	11380.45	28451.14

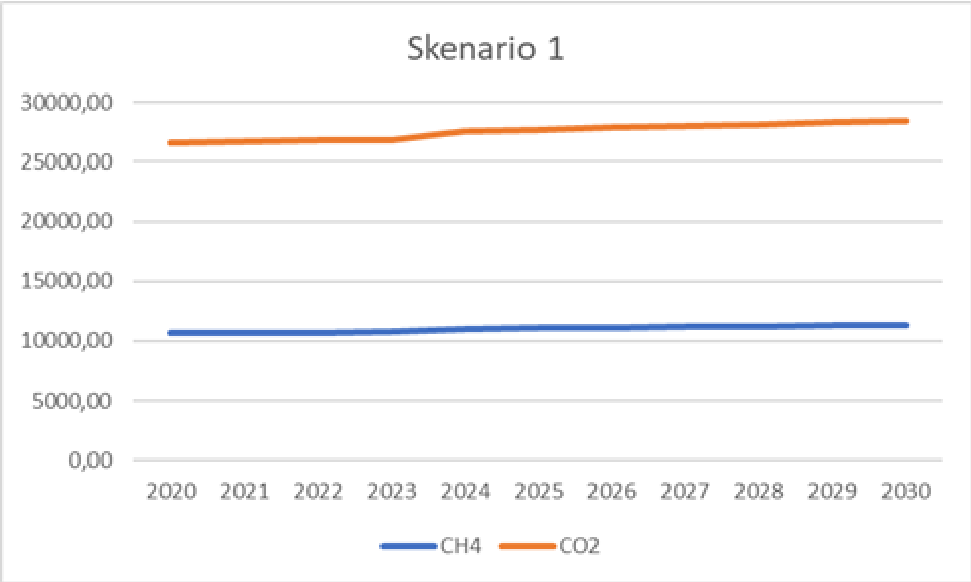

Fig. 1. CH_4 and CO_2 Gas Emission Graph Scenario 1

Emission Calculation Scenario 2

Scenario 2 considers the reduction process using the composting method and 3R containing food, garden and paper waste before going through the transportation process to the Benowo Landfill. It is estimated that the volume of waste that reaches the Benowo Landfill with research that calculates the amount of composting reduction of 34.34%, and 3R 13.59% at the TPS3R Super Depo Suterejo (Bahrah & Wicaksono, 2020). So, the weight of the waste is based on the composition of the waste, and the percentage of reduction is as follows:

Table 5. Projection of Waste Incoming in Each Process of Scenario 2

Year	Processing Process		
	Composting (tons)	***3R (ton)***	***Landfill (ton)***
2020	198284.09	78470.61	300659.66
2021	198814.25	78680.42	301463.54
2022	199344.40	78890.23	302267.42
2023	199874.56	79100.04	303071.29
2024	205306.17	81249.59	311307.29
2025	206343.09	81659.95	312879.58

Year	Processing Process		
	Composting (tons)	***3R (ton)***	***Landfill (ton)***
2026	207380.01	82070.31	314451.87
2027	208416.93	82480.67	316024.15
2028	209453.85	82891.02	317596.44
2029	210490.76	83301.38	319168.73
2030	211527.68	83711.74	320741.01

The scenario two process has significant potential in producing CH_4 and CO_2 emissions compared to the 3R sorting reduction process. So, the emission calculation uses the weight of the waste in the composting process, which is sorted based on the percentage of waste composition. This illustrates how greenhouse gas emissions from compost production in 2024 are calculated per CH_4.

Emissions = Σ (Mi x Efi) x 10^{-3} – R
= 466355.49 x 10^{-3} – 0
= 466.36 Tons or Gigagrams

Meanwhile, the remaining unmanaged waste disposed of in *landfills* can be calculated using the landfill formula, for example, in the composition (food waste).

DDOCm deposited (food waste) = MSW x DOC x DOCf x MCF
= 56714.15 Tons x 0.21 x 0.5 x 0.5
= 2054.04 Tons or Gigagrams

CH4 gas formed = DDOCm deposited x F x 16/12
= 5522.67 Tons x (0.5) x 16/12
= 1365.94 Tons or Gigagrams

CH_4 gas emissions in 2024 = (CH_4 generated − Rt) x (1 − OX)
(Accumulation of all compositions) = (4408.57 Tons – 0) x (1 – 0.1)
= 3967.71 Tons or Gigagrams

CH_4 and CO_2 emission calculations are obtained from the emissions produced in the composting and landfill processes in Scenario 2. In this combination, GHG emissions produced for both waste processing processes are recorded or inventoried comprehensively, as shown in the following table.

Table 6. Results of Calculation of Accumulated CH_4 and CO_2 Emissions for Scenario 2

Year	Accumulated Emissions			
	Composting		***Landfill***	
	Methane (CH_4)	***Carbon Dioxide (CO_2)***	***Methane (CH_4)***	***Carbon Dioxide (CO_2)***
2020	466,3555	1165.89	3967.71	9919,273
2021	467,6024	1169.01	3978.32	9945,794
2022	468,8493	1172.12	3988.93	9972,315
2023	470,0962	1175.24	3999.53	9998,837
2024	482,8711	1207.18	4108.22	10270.56
2025	485,3099	1213.27	4128.97	10322.43
2026	487,7487	1219.37	4149.72	10374.3
2027	490,1875	1225.47	4170.47	10426.17
2028	492,6263	1231.57	4191.22	10478.05
2029	495,0651	1237.66	4211.97	10529.92
2030	497,5038	1243.76	4232.72	10581.79

Source: Author Analysis (2024)

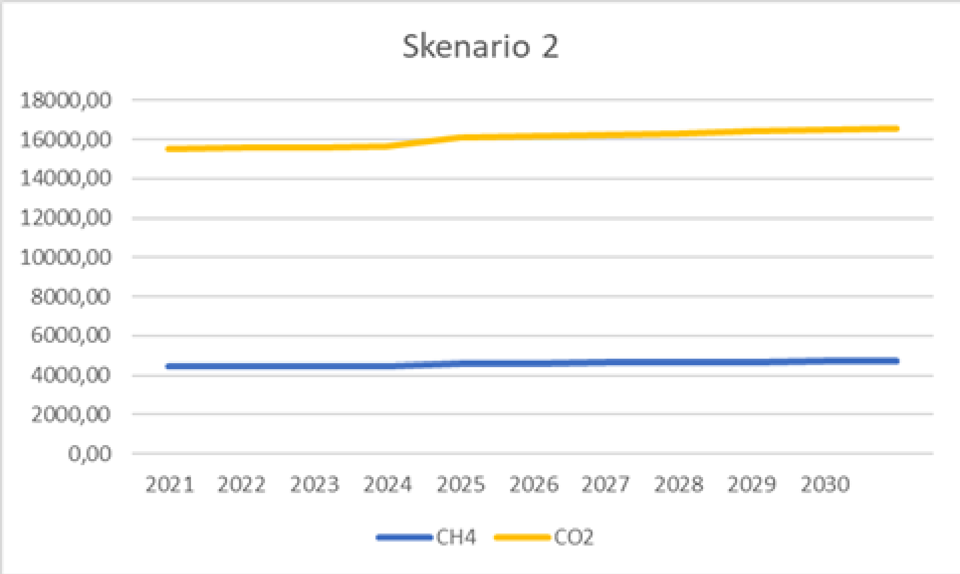

Fig. 2. Total CH_4 and CO_2 Gas Emission Graph Scenario 2

Scenario 3 Emission Calculation

In Scenario 3, methane gas emissions are calculated with the assumption that the waste is transported directly from its source to the Benowo TPA. In this TPA, the waste will be processed using gasification technology. Using gasification technology, emissions produced when waste is converted into energy can be significantly reduced, reducing the environmental impact caused. In this scenario, the waste to be gasified is 56% of the 44% disposed of in landfills. The rest of the waste is piled up elsewhere (Gani et al., 2025), so the comparison of the amount of waste generated is shown in **Table 7.**

Table 7. Projection of Waste Incoming in Each Process of Scenario 3

Year	Processing Process	
	Gasification (tons)	***Landfill (tons)***
2020	323352.05	254062.32
2021	324216.60	254741.61
2022	325081.15	255420.90
2023	325945.70	256100.19
2024	334803.31	263059.75
2025	336494.27	264388.35
2026	338185.22	265716.96
2027	339876.18	267045.57
2028	341567.13	268374.18
2029	343258.09	269702.78
2030	344949.05	271031.39

In Scenario 3, the gasification and landfill processes mainly focus on calculating carbon dioxide (CO_2) and methane (CH_4). CO_2 emission waste occurs in the gasification process without considering the processing of CO_2 emissions. The gasification process does not produce significant CH_4 emissions in line with IPCC guidelines. This approach is based on gasification, which is a thermal conversion technology. The following is an example of calculating CO_2 gas emissions in 2024:

CO_2 emissions in 2024 = IWt x CCW x FCF x EF x 44/12
= 19012.75 x 0.4 x 0.4 x 95% x 44/12
= 10596.44 Tons of CO_2

Conversion of CH_4 Emissions to CH_4 equivalent = CO_2 Emissions/CO_2 GWP
= 10596.44 / 28
= 378.44 Tons or Gigagrams

The total greenhouse gas emissions from the two waste disposal methods are shown in detail by combining methane and carbon dioxide emissions, as shown in **Table 8**.

Table 8. Results of Calculation of Accumulated CH_4 and CO_2 Emissions for Scenario 3

Year	Accumulated Emissions			
	Gasification		*Landfill*	
	Methane (CH_4)	*Carbon Dioxide (CO_2)*	*Methane (CH_4)*	*Carbon Dioxide (CO_2)*
2020	3027.55	105964.37	3352.78	8381.95
2021	3035.65	106247.69	3361.74	8404.36
2022	3043.74	106531.01	3370.71	8426.77
2023	3051.84	106814.33	3379.67	8449.18
2024	3134.77	109717.02	3471.52	8678.79
2025	3150.60	110271.15	3489.05	8722.62
2026	3166.44	110825.29	3506.58	8766.45
2027	3182.27	111379.43	3524.11	8810.29
2028	3198.10	111933.56	3541.65	8854.12
2029	3213.93	112487.70	3559.18	8897.95
2030	3229.77	113041.83	3576.71	8941.79

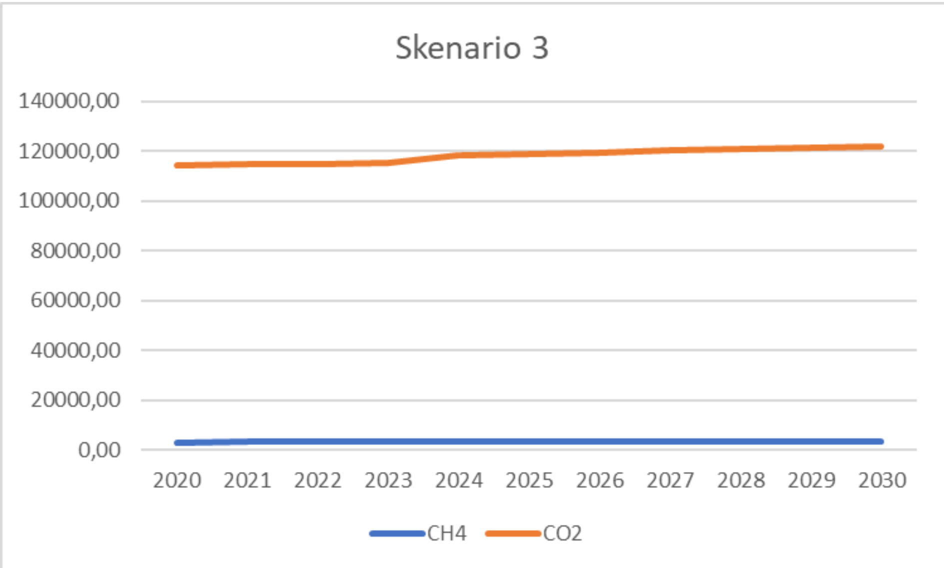

Fig. 3. Total CH_4 and CO_2 Gas Emission Graph Scenario 3

Comparison of Greenhouse Gas Emission Scenarios

Three scenarios are represented by the estimated methane gas releases and compared with each other.

Table 9. Comparative Accumulation of Emissions in Each Scenario

Emission	Scenario 1	Scenario 2	Scenario 3
CH_4	121334.5	50432.0	38133.7
CO2	303336.3	126080.0	433515.9

To strengthen the interpretation of the data in the tables and figures, this study analyzes the differences in greenhouse gas (GHG) emissions between three waste management scenarios using a comparative approach based on absolute numbers and percentage emission reductions. The calculation results show that the landfill scenario without treatment produces the highest methane (CH_4) emissions of 121,334.5 Gg, while the gasification scenario has the lowest methane emissions of 38,133.7 Gg, with a significant increase in carbon dioxide (CO_2) emissions due to the combustion process. To clarify the impact of each scenario, statistical significance tests can be applied to evaluate the differences in emissions between treatment methods, for example through ANOVA analysis or t-tests to compare the average emissions produced by each method. By applying this statistical approach, the study can provide stronger justification for the effectiveness of waste management methods in reducing GHG emissions and inform more data-driven policies for future waste management.

4. Conclusion

The inventory and projection of methane and carbon dioxide gas results for 2020-2030 through the IPCC tier II calculation from the 2006 IPCC Guidelines produced a total waste condition of the Benowo Landfill identical to the scenario. The landfilling scenario of 121,335 gigagrams of CH_4 has the highest CH_4 value, and the gasification scenario has the lowest CH_4 level of 38,133 gigagrams of CH_4. The gasification scenario has the highest CO_2 emission level of 433,515 gigagrams of CO_2, and the composting scenario has the lowest CO_2 level of 126,080 gigagrams of CO_2. At the same time, the highest GHG emissions (CH_4 and CO_2) come from the landfilling scenario, with the most significant CH_4 emissions and the most miniature CO_2. The gasification scenario produces the most significant CO_2 emissions and the smallest CH_4 because it uses an aerobic and combustion system.

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