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Estimation of Greenhouse Gas (GHG) emissions in waste management in Pekanbaru City, Indonesia

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ABSTRACT

Municipal waste production in Indonesia is rapidly increasing due to population growth and economic development, contributing significantly to greenhouse gas (GHG) emissions. This research aims to develop effective waste management scenarios for Pekanbaru City, focusing on reducing GHG emissions through integrated treatment methods. Employing a comprehensive methodology, the study estimates GHG emissions from various waste management practices, including biological, thermal, and mixed methods. The research utilizes a basic model to calculate emissions based on activity data and emission factors, exploring current practices and innovative strategies like Black Soldier Fly (BSF) larvae for organic waste treatment. Findings reveal that the Mix scenario, which combines multiple waste management processes, results in the most significant reduction of GHG emissions, achieving a net emission of 112,985.89 tons of CO_2-eq/year, compared to the existing scenario with 637,864.33 tons of CO_2-eq/year. The study identifies key emission hotspots, emphasizing the need for improved management of organic waste through composting and recycling. The implications of this research highlight the importance of adopting integrated waste management strategies to mitigate GHG emissions effectively. The findings provide actionable insights for policymakers, promoting sustainable practices aligned with the 3R hierarchy (reduce, reuse, recycle) and supporting targeted interventions that can enhance environmental sustainability in urban settings.

INTRODUCTION

Municipal waste production in Indonesia is increasing in line with the development of socio-economic conditions. Of the 268 cities/regencies throughout Indonesia, food waste from household waste and household waste will reach 29.28 million tons per year in 2022. About 40% of this volume is organic waste. Judging from the source, 32.3% of the generation comes from traditional markets, 36.1% from household waste, and 32.3% from business centers (SDGs achievement report, 2023). As much as 60–70% of waste produced in Indonesia is transported to landfills (landfills), while the remaining 30–40% is dumped into rivers, burned, or managed by the community itself (Kristanto & Koven, 2019).

The increase in population, accompanied by increasing economic growth, encourages an increase in production and consumption activities in the community (Du et al., 2024; Raihan & Tuspekova, 2022; Surya, Menne, et al., 2021; Surya, Suriani, et al., 2021; Xue et al., 2022). This has an impact on increasing the number, type, and diversity of garbage dump characteristics. Population growth, industry, urbanization, and economic growth, have resulted in a significant increase in the amount of urban solid waste worldwide (Khan et al., 2022; Maalouf & Mavropoulos, 2023; Shah et al., 2023; Velis et al., 2023; Voukkali et al., 2024). Like other cities in Indonesia, Pekanbaru City is an example of a major city in Indonesia. As for the waste generation in Pekanbaru City, in a year (2022) waste production reached 356,503.31 tons/year or 976.72 tons/day before entering the landfill (Kementerian Lingkungan Hidup dan Kehutanan, 2022).

In Pekanbaru, waste has not been handled optimally because there are many waste dumping sites without processes in open areas, open dumping systems are still used for final processing, and waste is collected and transported using transportation that requires fuel, shelter at TPS, composting, open burning, and various processes that require machines or heavy equipment that carry out almost all waste management processes producing greenhouse gas (GHG) emissions. To formulate an effective city waste management strategy, it is necessary to estimate the value of greenhouse gases in each waste management activity carried out and analyze and propose the best scenario that can be used as a guideline for the City of Pekanbaru.

In 2022, Pekanbaru City generated a total of 356,503.31 tons of waste, with 284,594.68 tons (79.83%) being successfully managed and 71,908.63 tons (20.17%) remaining unmanaged. While the majority of waste has been effectively handled, the presence of approximately 20% unmanaged waste highlights the need for improved waste management efforts to enhance future outcomes. The visual data is presented as follows:

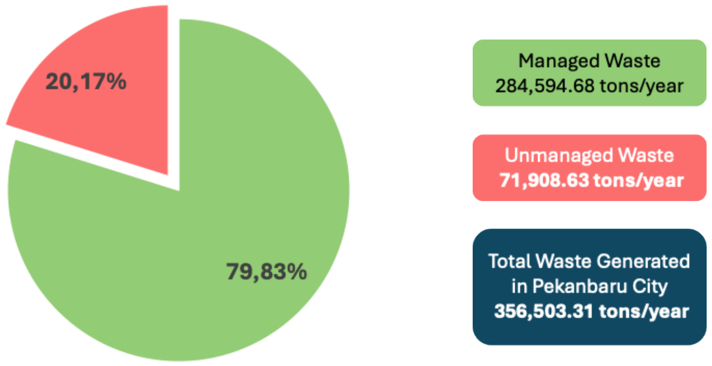


Figure 1. Pekanbaru City Waste Management Achievement Data (SIPSN, 2022)

Waste management in the city of Pekanbaru is the main challenge as the population and economic activities increase, according to SIPSN 2022 organic waste dominates 59% of the total generation, followed by paper/cardboard 12% and plastic 10%. Organic waste that is easily degradable requires proper processing, such as compost or energy, while plastic waste is a serious concern because it is difficult to decompose and has the potential to pollute the environment (Ayilara et al., 2020; Dilkes-Hoffman et al., 2018; Shen et al., 2020). Other components such as wood/twigs (3%), metal (2%), fabric, rubber/leather, glass 1% each, and other categories 11%, indicating a diversity of waste types that require different management approaches.

This research aims to develop a waste management scenario that focuses on reducing GHG emissions. The research contributes to the field of environmental sustainability by providing a comprehensive framework for developing waste management scenarios specifically aimed at reducing greenhouse gas (GHG) emissions. It enhances understanding of the relationship between waste management practices and emissions, offering actionable insights for policymakers and practitioners. By focusing on optimizing waste management strategies, the study addresses critical environmental challenges and supports the formulation of targeted interventions that can lead to significant reductions in GHG emissions. Additionally, the research underscores the importance of integrating various waste treatment technologies, thereby promoting a holistic approach to sustainable waste management that can be adapted to different urban contexts.

Regarding the research novelty, some previous research should be mentioned as well. The studies by Suryati et al. (2021), as well as by Sasmita (2022), primarily focus on estimating greenhouse gas (GHG) emissions from solid waste and domestic wastewater in Pekanbaru and Medan, respectively, providing valuable data but lacking comprehensive management solutions. In contrast, the current research offers an integrated framework for waste management in Pekanbaru, emphasizing various treatment methods, including biological and thermal processes, aimed at reducing GHG emissions. Notably, it introduces innovative strategies such as using Black Soldier Fly larvae for organic waste treatment, aligning with sustainable practices and the 3R hierarchy (reduce, reuse, recycle). This research presents a more actionable and holistic approach to effectively mitigate GHG emissions in urban environments.

METHOD

The study outlines a comprehensive methodology for estimating greenhouse gas (GHG) emissions in waste management for the city of Pekanbaru. It begins with the preparation phase, which involves selecting a city and conducting literature reviews to understand existing waste management conditions, including systems, challenges, and potentials. The process includes identifying waste composition and total generation through data verification and assumptions, ultimately leading to the determination of waste management scenarios from upstream to downstream.

Subsequently, the research employs a basic model for calculating GHG emissions, utilizing the formula:

$$\text{GHG emissions} = \text{Activity Data} \times \text{Emission Factor}$$

This approach is tailored to the waste sector, focusing on estimating emissions from waste processing and transport. Various scenarios are explored, including current practices, biological processing, thermal treatment, and mixed methods, which aim to optimize resource utilization and reduce landfill dependency. Each scenario is analyzed for its potential to minimize emissions, with detailed assessments of waste management processes.

The analysis highlights the impact of different waste management practices on GHG emissions, with a focus on avoidance strategies that can lead to significant reductions. For instance, recycling and the use of alternative energy sources from waste can mitigate emissions compared to traditional methods. The findings suggest that effective waste management not only reduces environmental impact but also provides economic benefits, emphasizing the need for ongoing research and implementation of best practices in waste management to enhance sustainability in Pekanbaru.

RESULTS AND DISCUSSION

Total GHG Emissions

After analyzing GHG emissions for each scenario, the author recapitulated GHG emissions in total per each scenario to analyze how effectively reducing GHG emissions from the alternative scenarios offered, as summarized by the author in the following table:

Table 1. Recapitulation of GHG Emissions From Reduced Efficiency (%) to BaU

Scenario	Gross ton CO_2-eq	Avoidance ton CO_2-eq	Net ton CO_2-eq	Efficiency Decline (%) to BaU
Existence (1)	652,534.44	-14,670.11	637,864.33	0% (baseline)
Biological (2)	242,365.27	-118,794.31	123,570.96	80.60%
Thermal (3)	351,640.67	-114,801.48	236,839.19	62.90%
Mix (4)	251,915.99	-138,930.10	112,985.89	82.30%

As the author displays in the graph GHG Emissions (tons CO_2-Eq) All Scenarios in 2022 Pekanbaru City as shown in the following image.

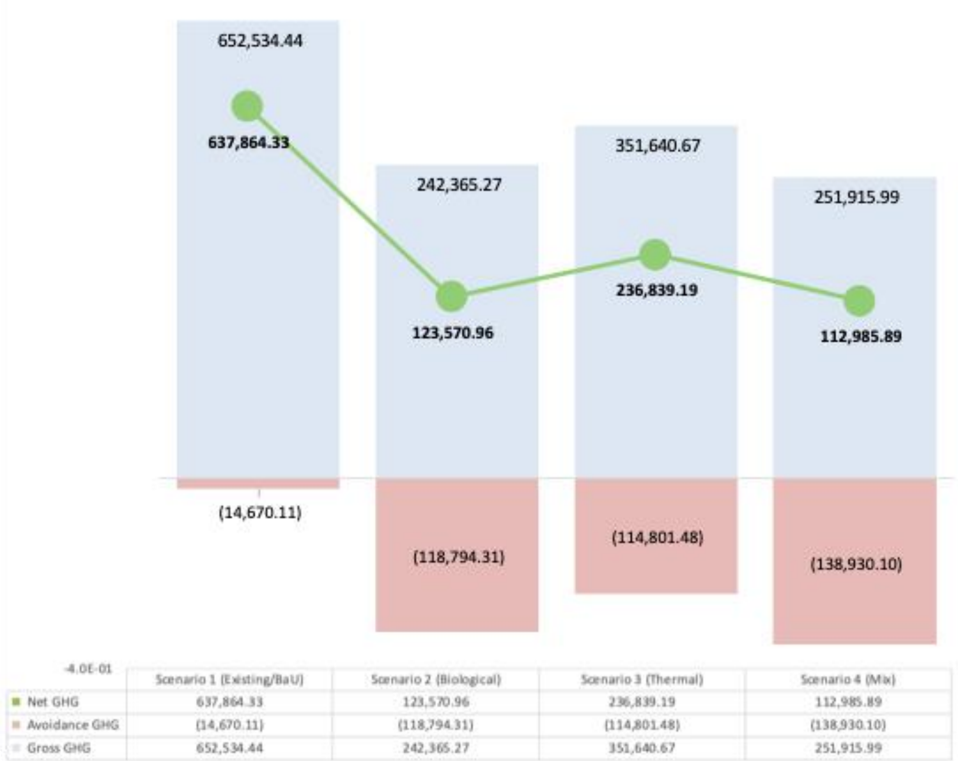


Figure 2. Graph of GHG Emissions (tons CO_2-Eq) All Scenarios in 2022 Pekanbaru City

Analysis of GHG Emissions and Hotspots in Each Scenario

Existing Scenario

The author recapitulated GHG Emissions in 2022 from the Existing scenario as shown in the following table.

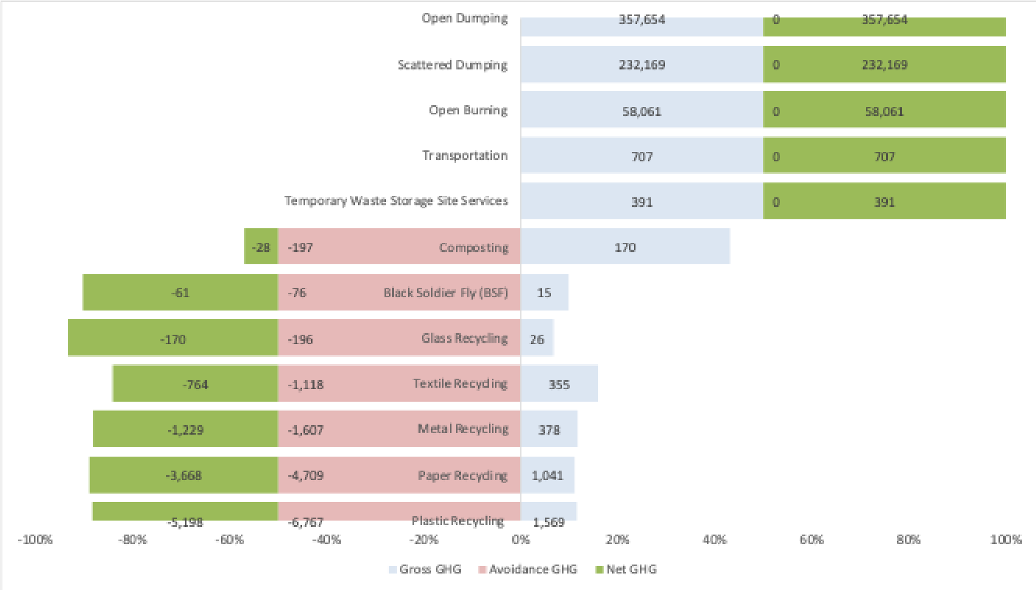


Figure 3. Graph of Highest to Lowest GHG Emissions (Gross, Avoidance, and Net) Existing Scenarios

Highest GHG Emission Hotspot

From the data in the table, the activities that contribute the most to GHG emissions are:

1) Open Dumping: 56.07% of total net emissions (Net GHG), with a value of 357,653.51 tons of CO_2-eq.
2) Scattered Dumping: 36.40% of total net emissions (Net GHG), amounting to 232,169.22 tons of CO_2-eq.
3) Open Burning: 9.10% of total net emissions (Net GHG), amounting to 58,060.85 tons of CO_2-eq.

These three categories account for a total of more than 90% of the total Net GHG, so they can be identified as "key hotspots" in waste management that generate significant emissions.

Analysis of GHG Emissions and Biological Scenario Hotspots

The author recapitulated GHG emissions in 2022 from the Biological scenario as follows, The data visualization in the graph is as shown in the following figure.

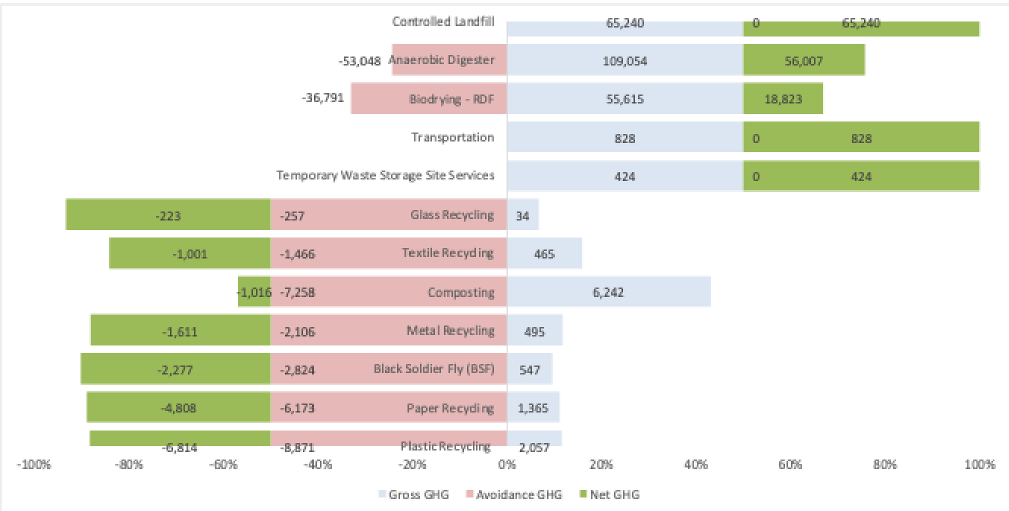


Figure 4. Highest to Lowest GHG Emissions Chart (Gross, Avoidance, and Net) Biological Scenarios

From the table and visualization of GHG Emissions data (Gross, Avoidance, and Nett) Biological Scenarios, the author makes a graph from the Highest GHG Emissions to the Lowest GHG Emissions to facilitate analysis and provide the following information:

Highest GHG Emission Hotspots in Biological Scenarios

The analysis reveals that Controlled Landfill is the largest contributor to net greenhouse gas (GHG) emissions, accounting for 52.80% of the total, which translates to 65,240.11 tons of CO_2-eq. While Controlled Landfill is better managed than open dumping, it still generates significant emissions, particularly methane (CH_4). However, it has a lower emission factor than open dumping, resulting in fewer overall emissions.

Anaerobic digestion follows as the second-largest source of net GHG emissions, contributing 45.32% of the total, or 56,006.67 tons of CO_2-eq. This process harnesses anaerobic decomposition to generate energy, yet it simultaneously produces GHG emissions, highlighting the complexity of balancing energy production with environmental impact.

Biodrying technology, specifically for producing Refuse-Derived Fuel (RDF), accounts for 15.23% of net GHG emissions, amounting to 18,823.37 tons of CO_2-eq. While this method effectively reduces the moisture content of waste to create RDF, it still emits GHGs due to the drying process and the energy consumption involved. Collectively, these findings underscore the need for improved waste management strategies to mitigate GHG emissions across various processes.

GHG Emission Analysis and Thermal Hotspot Scenario

The author conducted a recapitulation of GHG Emissions in 2022 from the Thermal Scenario as follows, data visualization in the graph as shown in the following figure.

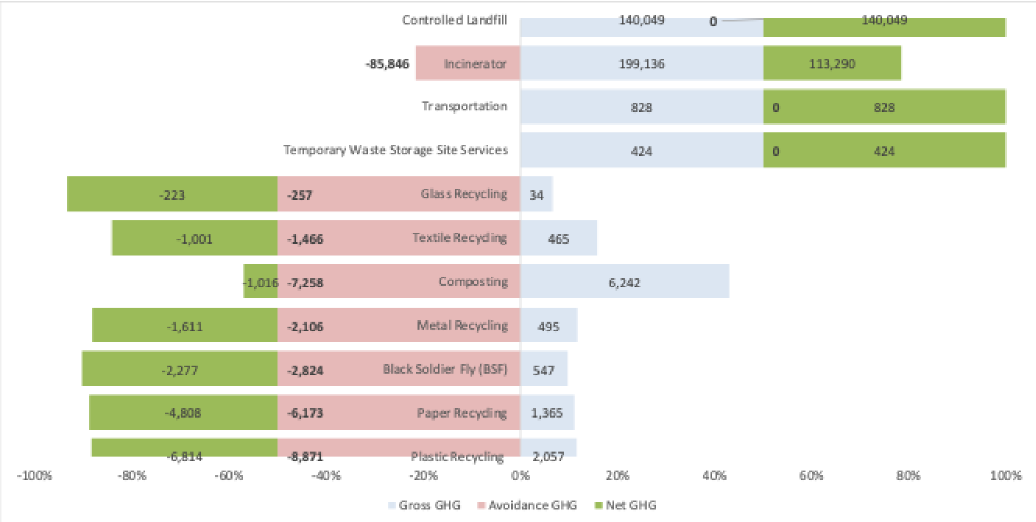


Figure 5. Highest to Lowest GHG Emissions Chart (Gross, Avoidance, and Nett) Thermal Scenarios

From the table and visualization of GHG Emissions data (Gross, Avoidance, and Net) Thermal Scenario, the author made a graph from the Highest GHG Emissions to the Lowest GHG Emissions in 2022 to facilitate analysis and provide the following information.

Highest GHG Emission Hotspots in Thermal Scenarios

Controlled Landfill is the largest contributor to net greenhouse gas (GHG) emissions, responsible for 59.13% of the total, which equates to 140,048.76 tons of CO_2-eq. Despite improvements in management practices, emissions from organic decomposition and methane gas (CH_4) continue to dominate, highlighting the ongoing environmental impact of landfill operations.

Incinerators represent the second-largest source of GHG emissions, accounting for 47.83% of the total, or 113,289.62 tons of CO_2-eq. This significant contribution underscores the environmental challenges posed by waste incineration, even as it is employed as a waste management strategy. Collectively, these findings emphasize the need for enhanced waste management practices to reduce emissions from both landfilling and incineration.

Incinerators produce GHG emissions, especially from waste burning that cannot be fully reduced through APDC, as well as providing other emissions outside of GHG that have the potential to increase pollution in the air

Analysis of GHG Emissions and Hotspot Mix Scenario

The author recapitulated GHG Emissions in 2022 from the Mix Scenario (Combination of Biological, Thermal, and Sanitary Landfill) as shown in the following table:

Table 2. Recapitulation of GHG Emission Calculations and Hotspot Mix Scenario

Waste Management Activities/Process	Scenario 3 Thermal ton CO_2-eq			(%) GHG Emissions Contribution from Net GHG
	Gross	*Reduction*	*Net*	
Transportation	827.91	-	827.91	0.73%
TPS Services	423.73	-	423.73	0.38%
Composting	6,242.23	(7,258.41)	(1,016.18)	-0.90%
Black Soldier Fly (BSF)	546.51	(2,823.51)	(2,277.00)	-2.02%
Plastic Recycling	2,056.76	(8,870.90)	(6,814.14)	-6.03%
Glass Recycling	34.16	(257.22)	(223.06)	-0.20%
Metal Recycling	495.02	(2,106.09)	(1,611.07)	-1.43%
Paper Recycling	1,365.11	(6,173.21)	(4,808.10)	-4.26%
Textile Recycling	464.86	(1,466.14)	(1,001.28)	-0.89%
Anaerobic Digester	109,054.36	(53,047.69)	56,006.67	49.57%
Gasification	89,496.59	(50,028.59)	39,468.00	34.93%
Sanitary Landfill	40,908.75	(6,898.34)	34,010.42	30.10%
Total	**251,915.99**	**(138,930.10)**	**112,985.89**	**100,00%**

The data visualization in the graph is as shown in the following figure.

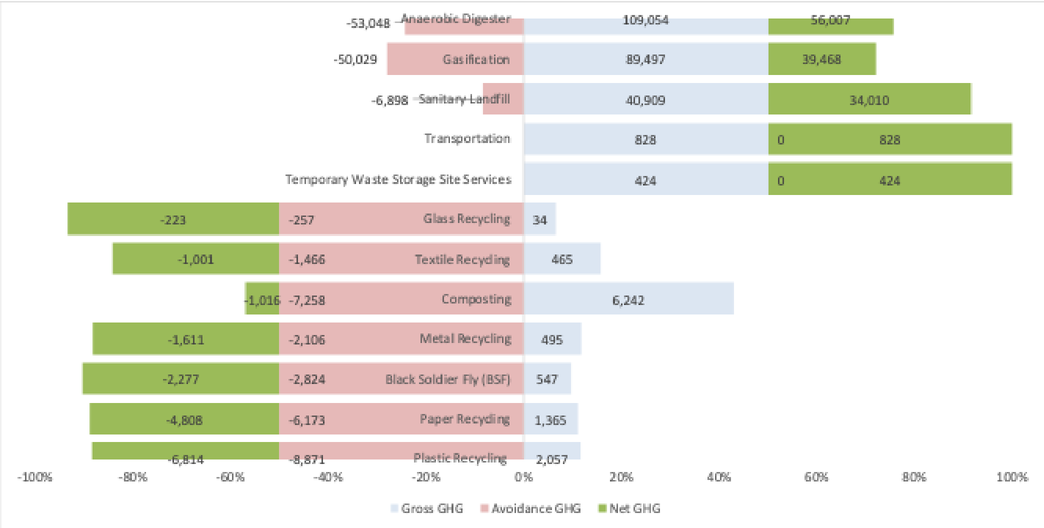


Figure 6. Highest to Lowest GHG Emissions Chart (Gross, Avoidance, and Net) Mix Scenario

From the tables and visualization images of GHG Emissions data (Gross, Avoidance, and Nett) of the Mix Scenario, the author made a graph from the Highest GHG Emissions to the Lowest GHG Emissions in 2022 to facilitate analysis and provide the following information:

Highest GHG Emission Hotspot in Mix Scenario

Anaerobic digestion accounts for a significant portion of net greenhouse gas (GHG) emissions, contributing 49.57% of the total, or 56,006.67 tons of CO_2-eq. This substantial figure is largely due to the high proportion of organic waste processed, which constitutes 40% of the total waste managed. While the anaerobic digestion process harnesses biological methods to generate energy from organic waste, it still results in GHG emissions, primarily from the methanization process and the potential for gas leaks.

Gasification follows as another major source of emissions, contributing 34.93% of total net GHG emissions, which amounts to 39,468.00 tons of CO_2-eq. This process involves the partial combustion of waste to convert it into energy, leading to emissions that arise during the conversion. Although some of these emissions can be mitigated through fossil fuel substitution, gasification still carries a relatively high emission factor compared to other waste management processes.

Sanitary landfills contribute 30.10% of net GHG emissions, totaling 34,010.42 tons of CO_2-eq. While this method is generally better managed than uncontrolled dumping, it still results in significant emissions. These findings highlight the need for improved waste management strategies across anaerobic digestion, gasification, and sanitary landfills to effectively reduce overall GHG emissions.

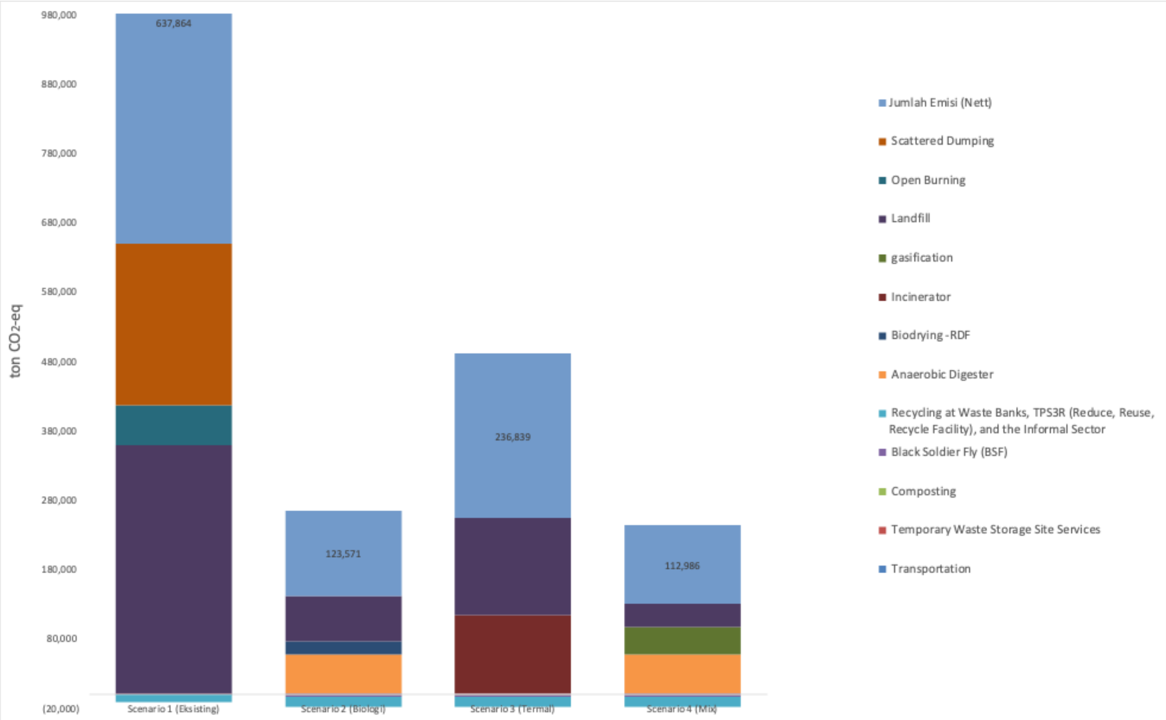
Although landfill management is more controlled than controlled landfill and strengthened by the use of LFG into electrical energy that is an avoidance of GHG emissions as a fossil fuel substitution, landfill disposal remains a significant source of GHG emissions due to methane emissions.

Analysis of Negative Values on Net GHG Emissions in All Scenarios

Greenhouse gas (GHG) emissions from waste management are one of the main concerns in climate change mitigation efforts. The waste management sector produces CO_2-eq emissions through the process of transportation, burning, disposal, and treatment of organic waste. To reduce environmental impacts, various waste management scenarios are designed to minimize net GHG emissions. As discussed in the analysis of each scenario. The author summarizes all the scenarios to see Net Negative GHG Emissions.

As previously stated regarding Net Emissions is the result of reduction between Gross emissions (the total amount of emissions produced) and Avoidance (avoided emissions). The author describes in the Recap Table and Graph of Net Negative GHG Emissions as shown in the following figure.

The graphic visual data is as shown below.



Notes on the Landfill Method of Each Scenario
Scenario 1 : Open Dumping;
Scenario 2-3 : Controlled Landfill;
Scenario 4 : Sanitary landfill (LFG Utilization)

Figure 7. Graph of net GHG emissions (CO_2-eq) from four waste management scenarios

In the figure above, the Negative Value on Net GHG Emissions shows the potential for mitigation to reduce GHG emissions where more emissions are successfully avoided than produced which is summarized in the explanation of the following process:

1) Composting (Scenarios 2, 3, 4): All scenarios (Biology, Thermal, and Mix) show Negative Values on Nett GHG Emissions for composting (-1,016 tons CO_2-eq). This is because the composting process reduces emissions from organic waste disposal at landfills (TPA) through conversion into products that can be used, such as organic fertilizers.
2) Black Soldier Fly (BSF), In Scenarios 2, 3, and 4, BSF technology also showed a Negative Value in Net GHG Emissions (-2,277 tons CO_2-eq). BSF is an organic waste treatment method that

produces low emissions due to the efficiency of waste conversion into biomass and waste reduction in landfills.

3) Recycling: In the Biological, Thermal, and Mix scenarios, recycling shows a Negative Value on sizable Net GHG emissions (-14,458 tons CO_2-eq). This shows that the informal sector and TPS3R significantly reduce emissions by diverting waste from landfills and contributing to considerable Emission Avoidance.

By prioritizing waste management processes that produce Negative Values on Nett GHG Emissions, such as composting, BSF, and Recycling, waste management can become more sustainable and support GHG emission reduction targets.

Analysis of GHG Emissions/ton MSW and tons of waste in Landfill in Each Scenario

Urban waste management is one of the significant sources of GHG emissions, especially CO_2, CH_4 (methane), and N_2O (nitrogen dioxide). Every ton of waste produced in big cities can contribute to different GHG emissions, depending on the management method used, namely disposal in landfills, thermal treatment, biological methods, or a combination of both as the author's scenario design in the 2022 Pekanbaru City study object. The recapitulation of GHG Emissions (Nett) to the waste generation of Pekanbaru City is conveyed as follows:

Table 3. Recapitulation of GHG/ton Emissions of MSW Pekanbaru City (Year 2022)

Information	Scenario 1 (Existing)	Scenario 2 (Biological)	Scenario 3 (Thermal)	Scenario 4 (Mix)
Emisi GRK (Nett) MSW(ton CO_2-eq) (A)	637,864.33	123,570.96	236,839.19	112,985.89
Waste Generation in Pekanbaru City (tons MSW) (B)	356,503.31	356,503.31	356,503.31	356,503.31
Emisi GRK /ton MSW(ton CO_2-eq) (A/B)	1.79	0.35	0.66	0.32

The GHG emissions per ton MSW (tons CO_2-eq) are shown in the following figure:

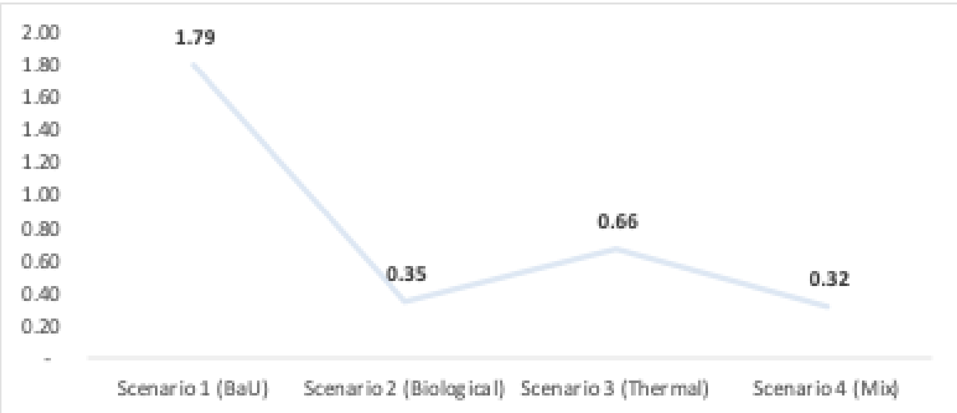


Figure 8. Graphic Amic GRK (Net)/to MSW (from Co_2-One)

In the table and figure above, the analysis can be conveyed as follows:

1) Emissions per ton of waste (A/B) are the highest in the existing scenario (1.79 tons of CO_2-eq/ton MSW), indicating the need for significant intervention in waste management.
2) The Biological Scenario (0.35 tons CO_2-eq/ton MSW) shows low emissions because it utilizes organic waste optimally. This scenario prioritizes biological management such as anaerobic digestion and biodrying for RDF products. GHG emissions are much lower than the existing scenario because this process minimizes methane emissions and uses organic waste into energy for electrical energy substitution from fossil fuels.
3) The Thermal Scenario (0.66 tons CO_2-eq/ton MSW) is better than the existing one but still produces quite high emissions because the combustion process has the potential for other emissions outside of GHG emissions. In addition, although the emissions are lower than the existing scenario, the thermal process produces relatively high emissions from the combustion process (although thermal energy can be harnessed).

4) The Mix scenario (0.32 tonnes CO_2-eq/ton MSW) is the most efficient, demonstrating the greatest potential in reducing GHG emissions through a combination of processes and LFG utilization from sanitary landfill designs

In addition, the author presents Greenhouse Gas (GHG) emissions generated from waste generation in landfills as hotspots in this study based on four scenarios as shown in the following table:

Table 4. Recapitulation of GHG Emissions/ton of Landfill Waste in Pekanbaru City (Year 2022)

Activities	Scenario 1 (BaU) Open Dumping	Scenario 2 (Biological) Controlled Landfill	Scenario 3 (Thermal) Controlled Landfill	Scenario 4 (Mix) Sanitary Landfil
GHG emissions in landfills (tons CO_2-eq) (A)	357,653.51	65,240.11	140,048.76	34,010.42
Waste Generation in Landfill (tons of garbage) (B)	243,301.71	53,475.50	114,794.07	53,475.50
Landfill (from Co_2-One) (A/B) from Amic GRK/ to Edah	1.47	1.22	1.22	0.64

The GHG emissions per ton of landfill waste (tons CO_2-eq) are shown in the following figure.

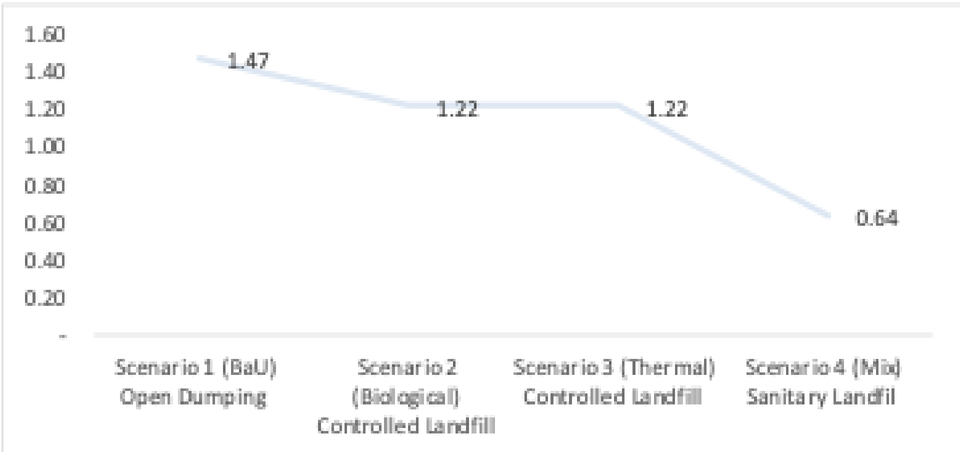


Figure 9. Graph of GHG Emissions (Nett) /ton of waste generated in landfills (tons CO_2-eq)

From the table and figure above, it can be conveyed that the Efficiency of Sanitary Landfill (scenario 4) shows the best level of efficiency with the lowest emissions (0.64 tons of CO_2-eq/ton of waste in landfills), illustrates the importance of the implementation of sanitary landfills in landfills because it produces the lowest emissions per ton of waste with a closed management process and the control and utilization of methane gas plays a major role in reducing GHG emissions.

The open dumping (BaU) produces the highest emissions per ton of waste because there is no management or process to reduce emissions. Methane from organic decomposition is the main contributor. The controlled landfill system (scenario 2-3) reduces emissions with better management than open dumping, because it is designed more controlled to reduce GHG emissions in landfills.

CONCLUSION

The study concludes that greenhouse gas (GHG) emissions from waste management in Pekanbaru City are significant, with the existing scenario (BaU) producing the highest emissions at 637,864.33 tons of CO_2-eq. Key hotspots identified include open dumping, scattered dumping, and open burning, which contribute over 90% of emissions. The research highlights that alternative scenarios, such as the Biological, Thermal, and Mix scenarios, could significantly reduce emissions, with the Mix scenario achieving an 82.30% reduction. The findings stress the importance of adopting comprehensive waste management strategies, including enhanced recycling, composting, and the utilization of Black Soldier Fly larvae, to effectively mitigate emissions. Recommendations for the Pekanbaru City Government include improving waste separation policies, investing in infrastructure for anaerobic digestion, and fostering community engagement through public awareness and collaboration with the informal sector. Future research should also explore the impacts of carcinogenic emissions and the long-term sustainability of proposed waste management practices.

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