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Greenhouse Gas Emission Estimation and Sustainable Municipal Solid Waste Management Development Strategy in Banda Aceh

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ABSTRACT

Domestic waste management activities produce greenhouse gases (GHG) that account for 3-4% of the world's total GHG sources. Waste processing such as the decomposition process in landfill activities, Aerobic and anaerobic processes in organic waste composting, and open burning waste also contributes to GHG emissions in the form of CO_2, CH_4, N_2O, and other gases. This study aims to integrate the IPCC 2006 (Tier 2) greenhouse gas inventory method with the Sustainable Balanced Scorecard (SBSC) technique to bridge the gap between emissions quantification and strategic environmental planning. This aims to support greenhouse gas emission reduction in the municipal solid waste management sector. The IPCC 2006 methodology was conducted to calculate greenhouse gas emissions, while the SBSC was utilized for transforming the emission assessment results into strategic environmental recommendations for emission reduction. This research uses secondary data obtained from DLHK3 Banda Aceh City and primary data in the form of the results of filling out questionnaires on 5 selected informants. GHG emissions of Banda Aceh City in the 2050 BaU scenario reached 11,752 Gg CO_2-eq, with landfilling producing the largest GHG of 10,755 Gg CO_2-eq. Meanwhile, if it is assumed that waste management conditions are in accordance with Scenario 2, the total GHG emissions in domestic waste management in 2050 will be 6,935 Gg CO_2-eq. Based on the SBSC analysis, recommendations are arranged based on the lowest performance values, namely, in the environmental perspective and the social perspective.

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1. INTRODUCTION

According to the World Meteorological Organization (2023), there has been an increase in the levels of current Greenhouse Gases (GHG) in the atmosphere compared to the pre-industrial era (before 1750), with carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) being the largest contributors, reaching 150%, 264% dan 124%. This growth in GHG levels causes the global warming phenomena, and be the controversial challenge across the globe (Keller, 2009). This phenomenon triggers various climate disasters such as extreme weather, heat waves, storms, droughts, floods, rising sea levels, and other hydrometeorological disasters (Isya et al., 2021). To tackle and prevent the worst impact of global warming for the sustainability of human life, all countries, including Indonesia, are committed to reducing their emission and achive (KLHK, 2024).

To achive this goal, Indonesia has to start with a national target in the Enhanced Nationally Determined Contribution (ENDC) with 29% unconditional reduction and 41% conditional reduction from the Business as Usual (BaU) scenario in all emission source sectors (Government of Indonesia, 2021). The sources of GHG emissions are determined by the IPCC (Intergovernmental Panel on Climate Change) into five sectors, namely Energy; Industrial processes and product use (IPPU); Agriculture, forestry and other land use (AFOLU); waste, and Other (e.g., indirect emissions) (KLH, 2012).

The waste sector is estimated to contribute 3-4% of global GHG emissions (BPPN, 2014) but in Indonesia, GHG emissions from waste reach 6,52 % (Kementerian Lingkungan Hidup dan Kehutanan, 2024), which is categorized into two sources: liquid and solid waste from both domestic and industrial sources (IPCC., 2019). All waste management activities, including waste processing at the source, waste transportation, and waste disposal in Landfills, have the potential to generate GHG emissions (Chaerul et al., 2020). Decomposition of waste during Landfill operations produces methane (CH4) (Sembiring, 2021), and the composting of organic waste can generate CH_4, C_2O, and N_2O emissions (Nurfadillah, 2022)However, CO_2 in the biological waste degradation process is not calculated because it is categorized as biogenic origin (Wargahadibrata et al., 2020). Additionally, the use of excavators and bulldozers in waste management at landfills also generates CO_2 emissions (Hutagalung et al., 2020). Beyond contributing to global warming, accumulated GHG emissions, particularly CH4, can cause explosions and fires if not properly managed (Yunitasari, 2014).

In Banda Aceh, the total waste generation is rising in line with its increasing population. While its geography condition make Banda Aceh highly potential risk of coastal erosion, tidal flooding, and land subsidence of up to 7 mm per year due to rising sea levels (USAID, 2016), a significant increase in air temperature also poses a risk to public health (BMKG, 2025). This situation causes mitigation efforts regarding global warming and climate change in the regions, especially in the waste sector, to be crucial thing to have.

Quantifying GHG levels is a fundamental thing for stakeholders and the government to support planning and implementing mitigation and emission reduction strategies (DLHK Banda Aceh, 2020), one of which is the waste management sector. Based on the 2020-2025 Banda Aceh City RAD-GRK Document, it is known that GHG emissions resulting from waste management activities in 2019 were 40,667 tCO2-eq or 40.667 Gg CO2eq per year. This calculation assumes the amount of waste generated at the Kampung Jawa landfill in Banda Aceh City is 87,084 Gg (DLHK Kota Banda Aceh, 2020). Although an inventory of GHG emissions from the waste sector has been conducted in this document, the study has not integrated the results of long-term emission quantification (until 2050), which is related to the net-zero waste emissions target in 2050 and the framework for formulating a sustainable waste management strategy. This gap prompted research to estimate GHG emissions using the IPCC 2006 method and formulate a mitigation strategy using the Sustainability Balanced Scorecard (SBSC) approach.

The issues of waste management and the resulting GHG emissions constitute a complex problem involving various stakeholders such as the government, relevant institutions, and the public (Lingga et al., 2024). Because of that, a policy strategy for waste management is needed. The absence of a holistic understanding of intragrated solid waste management does not allow measurement of the level waste hierarchy making it incapable of evaluating the performance and SBSC method is an important tools to measure the performance (Aly &Mansour, 2017). One of the best methods used to map strategies based on performance measurements across financial, non-financial, and sustainability aspects is the Sustainable Balanced Scorecard (SBSC) (Alamsyah et al., 2019). According to Tsai et al. (2020). the SBSC method can be applied in measuring the performance of urban waste management because it can map strategies based on performance data of the region's existing conditions, integrated with each SBSC perspective. In SBSC, each measurement perspective drives performance in the next set of measurements. Overall, each performance indicator is interconnected and contributes to measuring the achievement of organizational strategy and corporate value creation (Figge et al., 2002).

This study is limited to calculating GHG emission estimation from Domestic solid waste in Banda Aceh without calculating the emissions produced by wastewater and industrial waste. There is no sampling (direct measurement), so the data for analysis are from local institutions such as

DLHK3 Banda Aceh (secondary data). This study focuses on GHG estimations from waste management activities and formulates strategic recommendations that are expected to provide solutions to the problems in the city of Banda Aceh. This study applies a BAU scenario based on baseline data from 2015–2024 to project greenhouse gas emissions through 2050 using the IPCC 2006 methodology.

2. METHODS

2.1 Time and Location

This research was conducted over an eight-month period, from October 2024 to June 2025, starting from initial observations and problem formulation in October, then continuing with title submission, literature study, data collection, and data analysis. This research was conducted in Banda Aceh, which involved government institutions such as DLHK3 Banda Aceh, BAPPEDA Banda Aceh, Municipal Solid Waste Disposal (TPA), Waste Bank, and TPS3R.

2.2 Data Collection

Data collection is a key factor in analyzing emissions from waste management activities. Data collection in this study includes:

2.2.1 Secondary data

Secondary data were obtained from documents and reports from the Banda Aceh Environmental and Sanitation Department (DLHK3). The required data include: waste generated by the community, waste weighbridge data at the landfill, waste composition, percentage of waste services, percentage of waste dumped at the landfill from the total daily waste generation, percentage of open waste burning, number of waste management facilities (waste banks and Municipal Solid Waste disposal), waste composition, and percentage of organic waste composting.

2.2.2 Primary Data

The primary data from this study are the results of filling out questionnaires by 5 experts (expert judgment) involving the Banda Aceh Environmental Department (DLHK3), the Banda Aceh City Development Planning Department (BAPPEDA), and waste management facility managers to obtain data on perceptions and assessments related to recommendations for GHG reduction in waste management. The Expert Judgment approach in this study serves to complement the unavailability of secondary data needed in waste management. The questionnaire was developed based on the research perspective and the indicators studied. Although the number of experts was relatively limited, all participants met the selection criteria, such as having a reputation in the field being researched, having an understanding and experimental experience in the field being researched, a balanced and neutral view (Cooke, 1991).

2.3 Data Analysis

Data analysis in this study focused on two different aspects, namely the technical aspect for quantifying GHG emissions and the non-technical aspect for determining the strategic recommendation to reduce emissions from the waste management sector based on key performance indicator analysis in SBSC.

2.3.1 Technical Aspect

In the technical aspect, the IPCC 2006 method was utilized in volume 5, which provides ways to inventory in the waste management sector, particularly for domestic waste. No instrument validation was required because this study did not employ questionnaires or measurement instruments. This method was approved by the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) in these Guidelines. This study uses the tier 2 IPCC 2006 method, based on accurate data and statistical collection for calculating the largest GHG produced from waste management in Banda Aceh, such as carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O)(Wargahadibrata et al., 2020).

a. Biological waste degradation Emission

The biological waste degradation process includes composting and other biological processes involving microorganisms in the decomposition of organic material under aerobic and anaerobic conditions (Nurfadillah, 2022). This is the formula used to estimate CH_4 and N_2O emissions.

$$CH_4 = \sum_i (M_i \times EF_i) \times 10^{-3} - R \quad (1)$$

$$N_2O = \sum_i (M_i \times EF_i) \times 10^{-3}$$

Where:

M_i = Mass of composted organic waste
EF_i = Emission Factor
R = Amount of methane recovered

b. Landfill Emission

Calculation of GHG emissions in landfill waste disposal utilizes the IPCC 2006 Guidelines. The method used in this study is the FOG (First Order Decay) method.

$$CH_4\ (T) = [\sum CH_4\ generated_{i.t} - R_T] \times (1 - OX_T) \quad (2)$$

$$CO_2 = CH_4 \left(\frac{1-F}{F} + OX\right) \times \frac{44}{16}$$

$CH_4\ generated_{i.t}$ = the among of CH4 formed in the year (T)
R_T = amount of methane recovered (based on landfill type)
OX = Oxidation factor

c. Emission caused by Open Burning Emission

The amount of GHG emissions from open burning is determined by the product oxidation factor, the conversion factor to CO2, and the projected carbon content. The amount of oxidized fossil carbon in the waste forms the basis for data on the emission factor and the amount of waste burned openly.

$$CO_2 = M_i \times \sum_i (WF_i \times dm_i \times CF_i \times FCF_i \times OX) \times \frac{44}{12} \quad (3)$$

$$CH_4\ or\ N_2O = \sum_i (M_i \times OX_i) \times 10^{-6}$$

M_i = Mass of waste (*total*)
WF_i = Mass of waste from *i* (*wet weight of open burning*)
dm_i = Dry matter fraction in waste
CF_i = total carbon content
FCF_i = Fraction of fossil carbon in total carbon

2.3.2 Non-Technical Aspect

Non-Technical Aspect contains the determination of recommendation strategies for reducing GHG emissions from municipal solid waste in Banda Aceh, based on data analysis utilizing the Sustainable Balanced Scorecard (SBSC) method. The SBSC method adjusts 5 perspectives would linked with sources and recovery of GHG emissions, such as: Environmental perspective, internal processing perspective, financial perspective, social perspective, and development/learning perspective (Johannes, 2009).. The stages of data analysis using the SBSC method are:

a. Determine the objectives or goals to be achieved
b. Identify the SBSC perspective applied
c. Determine strategic objectives and Key Performance Indicators (KPIs) for each perspective. Key performance indicators serve to identify current waste management performance (reality) (Epstein & Wisner, 2001), which will then be compared with existing national and local targets.
d. Calculate the weighting of each perspective.
   - Analysis KPI score, with data polarization (maximize or minimize)

Maximize polarization

$$KPI\ performance\ index = \frac{Realization}{target} \times 100\% \quad (4)$$

Minimize Polarization

$$KPI\ performance\ index = \left[1 + \left(1 - \frac{realization}{target}\right)\right] \times 100\% \quad (5)$$

- Strategic objective score analysis (NSS)

$$NSS = \sum Indeks\ capaian\ IKU \times bobot\ IKU) \quad (6)$$

- Perspective performance score (NKP)

$$NKP = NSS \times (\%)\ bobot\ perspektif \quad (7)$$

e. Determining strategic initiatives
Strategic initiatives are the goal of weighting and comparing the performance of previously established KPIs. After assessing each perspective, the problem and its solution are identified in the form of recommendations deemed accurate. The entire strategic initiative development process is then depicted on a strategy map to facilitate visualization of the chosen strategy formulation. The causal relationship (cause-effect) between perspectives will be depicted on a strategy map (Moller & Schaltegger, 2005). The flow diagram shows the arrangement of the strategic map in Figure 2.

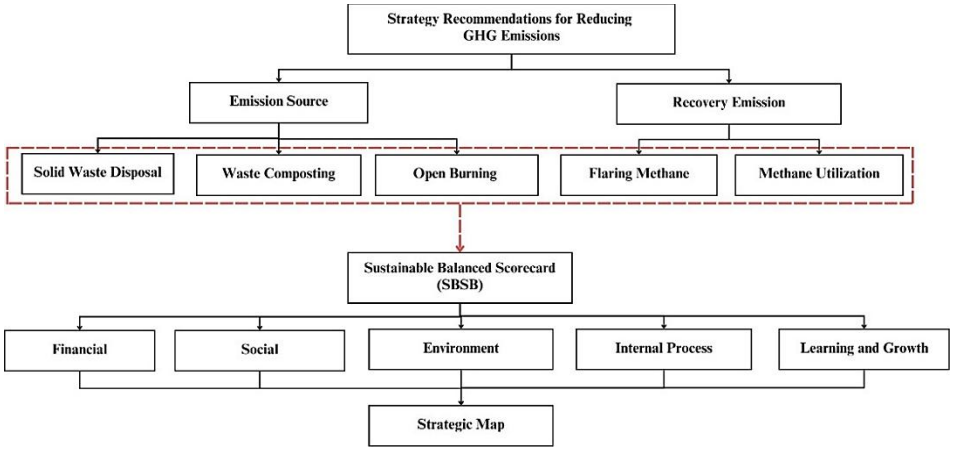


Figure 1. The flow diagram for the strategic map

3. RESULT AND DISCUSSION

3.1 Result

3.1.1 Existing Conditions of Waste Management

Waste management in Banda Aceh refers to Qanun Number 1 of 2017 concerning Waste Management in Banda Aceh, which divides the waste service zone into three parts, namely: Zone I: Banda Raya, Jaya Baru, and Meuraxa Districts; Zone II: Kuta Alam, Syiah Kuala, and Ulee Kareng Districts; and Zone III: Lueng Bata, Baiturrahman, and Kuta Raja Districts. The Government of Banda Aceh targets to maximize the 3R principle (reduce, reuse, and recycle) to manage its waste, because transferring waste to the Blang Bintang Regional Landfill cannot be a long-term solution for Banda Aceh City, due to the high annual landfill costs. The Banda Aceh City Government must allocate at least IDR 1.1 billion annually to divert waste to the regional landfill (DLHK, 2025). Table 1 is the percentage data on the distribution of domestic waste management in Banda Aceh City. Furthermore, the percentage of waste composition can be seen in Table 2 (PEMKOT Banda Aceh, 2019).

Table 1. Domestic Waste Distribution Data

No.	Waste Processing	Percentage (%)
1.	Composting	4,00
2.	Recycling	12,40
3.	Landfill	9,18
4.	Open Burning	0,80
5.	Transfer	72,04
6.	Unmanaged	1,58

DLHK3 Banda Aceh, 2025

Table 2. Waste composition

Waste Component	Percent (%)
Food waste	58
Paper	4
Garden waste	12
Textile	2
Rubber	1
Plastic	19
Metals	1,53
Glass	0,15
Others	0,97

SSK Banda Aceh, 2019

3.1.2 Population Projections and Waste Generated

This research needs the population projection in Banda Aceh until 2050 for estimating the amount of waste generated and its emissions. Population projections were conducted to predict the future population. The population projection time series was compared to the baseline (history) for waste generation calculations from 2015 to 2024, which was sourced from the National Statistics Centre Institution (BPS). Meanwhile, the waste generation data comes from the annual report of the Environmental Service. waste generation in 2015-2024 is shown in the **table 2**. Three projection methods were used: arithmetic, geometric, and exponential, selected based on the results of comparing the correlation coefficient values closest to 1 and the smallest standard deviation. The smallest standard deviation is found in the arithmetic method, with a correlation factor is 0.99993. Therefore, the method used to calculate the population projection of Banda Aceh is the Arithmetic method. **Figure 3** is a graph of the results of the population projection calculations for Banda Aceh City from 2025 to 2050.

Table 3. Waste Generation in 2015-2024

Year	Population	Waste generation (tons/prs/year)	Waste generation	
			Tons/year	Gg/year
2015	250.303	0,232	58.135,74	58,136
2016	254.904	0,239	60.888,07	60,888
2017	259.913	0,255	66.323,92	66,324
2018	265.111	0,305	80.745,73	80,746
2019	270.321	0,273	73.728,37	73,728
2020	252.899	0,319	80.657,82	80,658
2021	255.029	0,343	87.377,19	87,377
2022	257.637	0,354	91.306,46	91,306
2023	261.969	0,356	93.370,54	93,371
2024	262.960	0,360	94.679,63	94,680
Waste generation (max)		**0,360**		

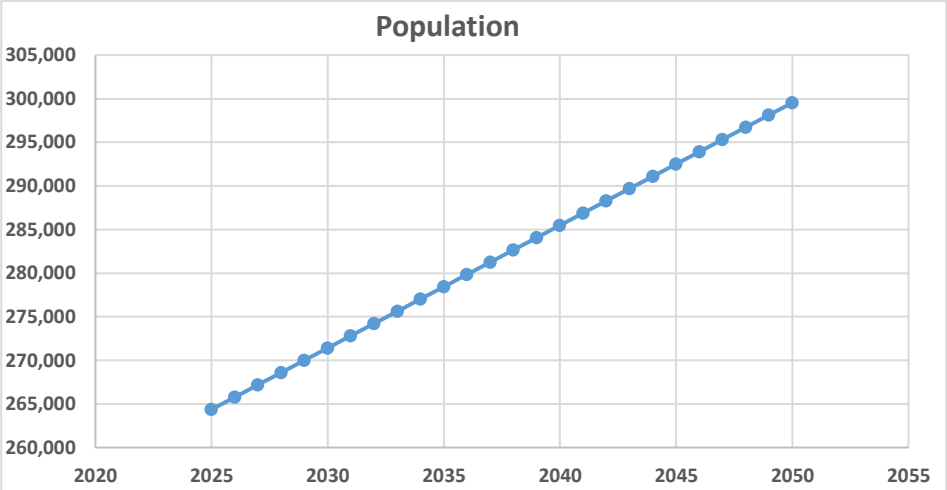


Figure 2. Banda Aceh Population Projection

After calculating the population projection, the waste generation projection continues to be calculated. To determine the amount of waste generated in 2050, a calculation is determined by multiplying the projected population in 2050 by the amount of waste generated, which is 0.360 tons/person/year. Domestic waste generation from 2025 to 2050, based on the projection results, can be seen in Table 4.

Table 4. Projection of waste generation in Banda Aceh

Year	Population	Waste Generated (ton/person /year)	Waste Generated	
			Ton/year	Gg/Year
2025	264.366	0,360	95.185,99	95,19
2030	271.398		97.717,76	97,72
2035	278.430		100.249,54	100,25
2040	285.461		102.781,31	102,78
2045	292.493		105.313,09	105,31
2050	299.526		107.844,86	107,84

3.1.3 Calculating GHG Emission from Domestic Waste Sector

Based on domestic waste distribution data (in Table X), it is known that the majority (72,04%) of Banda Aceh's domestic waste is transferred to the regional landfill; consequently, the amount of waste that is disposed of in Banda Aceh landfill is only 9,18% of the total domestic waste produced. The percentage of composting and recycling of waste in Banda Aceh City reached 4% and 12.40% of the total waste; however, the amount of unmanaged waste was 1.58%, and the percentage of open burning reached 0.8% of the total domestic waste in Banda Aceh City. In calculating GHG emissions using the IPCC Tier 2 method, only data on waste composting, open waste burning, and landfills are used to estimate the amount of emissions produced (United Nation Environment Program, 2010). Meanwhile, emissions generated by waste transferred to regional landfills are categorized as Aceh Besar Regency emissions.

The calculation of the amount of emissions in this study uses 2 scenarios to estimate the extent of the influence of the implementation of the national waste reduction target (Net Zero waste emission) and the Banda Aceh City Government target on emission sources from domestic waste. Table x shows the projection of the distribution of waste in Banda Aceh City based on emission sources in waste management using the scenario of Odor or without intervention (1) and the scenario with intervention to achieve the ideal waste management target (2). **Table 5** shows the projected distribution of waste generation in Banda Aceh City based on the management methods in Scenario 1 and Scenario 2.

Table 5. Distribution of Waste Generation (Scenario Based)

Scenario	Year	Waste total (Gg)	Composting		Open Burning		Landfill	
			%	Gg/year	%	Gg/year	%	Gg/year
1	2025	95,186	4	3,807	0,80	0,757	9,18	8,736
	2050	107,845	4	4,314	0,80	0,858	9,18	9,897
2	2025	95,186	5	4,759	0,77	0,733	8,68	8,262
	2050	107,845	30	32,352	0,02	0,022	0,18	0,194

3.1.4 Greenhouse Gas Emission Scenario 1 (Business as Usual)

Scenario 1 represents the Business as Usual (BaU) condition, which assumes that future conditions will be the same as the past, without any technological improvement or policy intervention (BAPPENAS, 2014) as the baseline for evaluation. In this scenario, the percentage of domestic waste treated remains constant throughout the projection period, with composting (4%), Open burning (0,80%), and landfill (9,18%). Even though the percentage of emission sources remains constant, the amount of emissions will continue to increase in waste generation in line with population growth and urban activities (Samin et al., 2018). ***Table 6*** is the result of the calculation of greenhouse gas emissions (GHG) resulting from composting, landfill, and open waste burning activities.

Table .6 results of GHG calculations for scenario 1

Year	Gg CO_2-eq			Total (Gg CO_2eq)
	Composting	Landfill	Open Burning	
2025	0,721	8,492	0,159	9,371
2030	0,740	9,217	0,163	10,120
2035	0,759	9,704	0,167	10,630
2040	0,779	10,096	0,171	11,046
2045	0,798	10,440	0,175	11,413
2050	0,817	10,755	0,180	11,752

Based on *Table 6*, there is an increase in the amount of GHG emissions every year from various waste management methods from 2025 to 2050. Waste disposal in landfills contributes the largest amount of emissions, reaching 8,492 Gg Co_2-eq in 2025, which then increases again to 10,755 Gg CO_2-eq in 2050. Furthermore, in the composting process, there is an increasing number of emissions from 0.721 Gg CO_2-eq to 0,817 Gg CO_2-eq in the same period. Open burning activities in Banda Aceh also produce greenhouse gas emissions, reaching 0.180 Gg CO2-eq in 2050.

3.1.5 Greenhouse Gas Emissions Scenario 2

Scenario 2 is designed as a comparison scenario with Scenario 1 (BaU), assuming ideal conditions where the government's strategy has been implemented and meets its targets. Scenario 2 focuses on reducing the percentage of domestic waste dumped in landfills and open burning as the main sources of GHG emissions, and also plans to increase the percentage of composting and recycling. Furthermore, there is a reduction in the amount of waste dumped in the Gampong Jawa landfill and open burning, which will affect the distribution of domestic waste management in Banda Aceh City. ***Table 7*** is the result of the calculation of greenhouse gas emissions (GHG) resulting from composting, landfill, and open waste burning activities.

Table 7. Results of GHG calculations for scenario 2

Year	Gg CO_2-eq			Total
	Composting	Landfill	Open Burning	
2025	0,901	8,492	0,154	9,547
2030	1,851	7,786	0,127	9,764
2035	2,848	5,931	0,099	8,877
2040	3,893	3,634	0,069	7,597
2045	4,987	1,470	0,038	6,494
2050	6,128	0,803	0,005	6,935

3.1.6 Non-Technical Aspect

In determining strategic recommendations, the Sustainable Balanced Scorecard (SBSC) method is used in five main perspectives, namely: environmental perspective, internal process perspective, financing perspective, social perspective, and learning/development perspective. After measuring each Sustainable Balanced Scorecard perspective based on the formulated strategic objectives and indicators, the next step is to assess waste management performance by multiplying the calculated score of each perspective by a predetermined weight percentage. The results of the overall assessment of the SBSC perspective can be seen in **Table 8.**

Table 8. Overall performance assessment results perspectives

No	Perspective	Performance Achievement Value	NKP
1	Environment	55,21	11,04
2	Internal process	76,10	15,22
3	Financial	83,96	16,79
4	Social	64,33	12,87
5	Learning and Growth	89,38	17,88
Total			**73,80**

3.1.7 Strategy map

The strategy map in the Sustainability Balanced Scorecard (SBSC) method serves to represent the cause-and-effect relationship across all perspectives toward strategy objectives. The strategy map facilitates the translation of objectives in a structured and interrelated manner, thus facilitating communication, implementation, and measurement of performance indicators (Wulandari et al., 2016). Based on the analysis of strategic objectives and KPI scores, problems and recommendations are obtained, which can be seen in the strategy map in **Figure 3.**

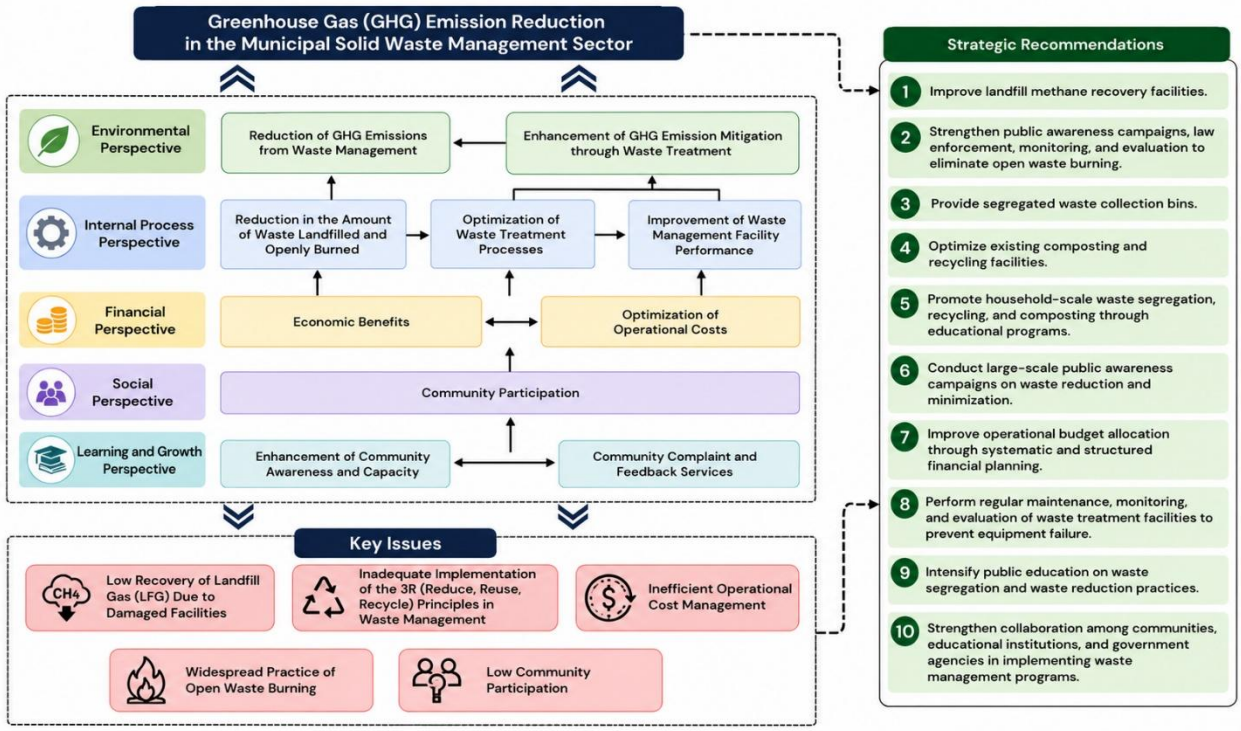


Figure 3. Strategy Map

3.2 Discussion

Based on Table 1, the percentage of domestic waste management in Banda Aceh City for composting is 4%, and recycling is 16%. This number is still relatively low compared to the regional targets for composting and recycling of 6% and 18% per year, respectively (DLHK3 Banda Aceh, 2020), Efforts to improve are still very much needed because the majority of domestic waste is still transferred to the regional landfill in Blang Bintang, that need the high annual landfill costs (DLHK, 2025). Meanwhile, the percentage of waste dumped in the Banda Aceh City Landfill is 9.18%, and the percentage of open burning reaches 0.8%. The distribution data for waste management in Table 1 and the waste composition data in Table 2, which come from the 2019 Banda Aceh City Sanitation Strategy document (SSK Banda Aceh, 2019), will be used as the basis for calculating the production of GHG emissions in Banda Aceh City. Furthermore, the results of the population projection calculation in Figure 2 show that the population of Banda Aceh City will increase every year. In 2050, the population of Banda Aceh City will reach 299,526 people. The results of the population projection calculations are used to calculate the amount of waste generated in Banda Aceh City in Table 4.

Table 5 shows the projected distribution of waste generation in Banda Aceh based on two scenarios that are planned. In scenario 1, the percentage of domestic waste management is assumed to remain constant from 2025 to 2050, thus maintaining the same level of waste as a source of emissions. Conversely, in scenario 2, a significant change in the percentage of waste management is assumed, reflecting the achievement of sustainable waste management targets. The percentage of waste composted increases until 2050, while in the same period the percentage of waste landfilled and openly burned waste decreases. This decrease indicates a change of methods that potentially produce GHG to more environmentally friendly waste management.

Based on the calculation results of GHG emissions in Banda Aceh City using the BaU scenario in Table 6, the amount of emissions in the waste sector in 2025 is 9.371 Gg CO_2-eq, while in 2050, it is predicted that the amount of GHG emissions will experience a significant increase to reach 11.752 Gg CO_2-eq. Although there are the rise number of GHGs in Banda Aceh, it is still lower compared with several cities in Indonesia, such as Jayapura and Batu city from waste is estimated to reach 24,087 Gg CO2-eq (Rismawati, 2017) and 11,686 Gg CO2-eq in 2030 (Lestari, 2017). This increasing in line with the LTS-LCCR (2050), which states that the accumulation of GHG from waste

management in the atmosphere is predicted to continue to increase due to population growth, economic growth, lifestyles, and the lack of mitigation efforts from related stakeholders (Government of Indonesia, 2021). Moreover, methane recovery in composting and landfill activities scored zero (0%) based on the current situation in the Banda Aceh landfill, because there is no methane reduction factor.

The largest GHG emissions in 2050 come from waste disposal activities in landfills with 10.755 Gg CO_2-eq, caused by the highest Methane (CH4) production from the anaerobic decomposition process of waste in the landfill. Furthermore, in biological processes such as composting, organic waste can also produce CH_4, CO_2, and N_2O, but Co_2 is not included in net emissions measurement because it is categorized as biogenic emissions (Mohareb et al., 2011). Besides producing GHG emissions, open burning can also produce harmful compounds for human health, including CO, NOx, SO2, volatile organic compounds (VOC), Particulate Matter2.5 (PM2.5), and PM10 (Das et al., 2018). These compounds come from oxidized fossil carbon in openly burned waste, can worsen air quality, and contribute to the global warming effect (UNICEF, 2024). The amount of emissions from waste management activities is inversely proportional to the national target of Near Zero Waste Emission (NZE 2050) based on the Indonesia Long Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR), which targets 0 emissions from open waste burning activities and 0% waste disposal in landfills other than residual waste and unusable waste. This target emphasizes the implementation of paper waste recycling and organic waste composting up to 90% of the total generation. This is because GHG emissions due to waste disposal mostly come from the decomposition of paper waste and organic waste in Landfills (KLHK, 2024).

In addition, GHG inventory reporting requires the same unit, CO_2-eq (IPCC, 2006). Therefore, in calculating emissions using the IPCC 2006 method, a comparison is made between the ability of GHGs to trap solar heat in the atmosphere and CO_2, commonly known as the Global Warming Potential (GWP) (IPCC,2007). This study used the AR4 standard, with a GWP ratio of CH_4 and N_2O of 25 and 298, respectively.

This scenario was developed based on the local government's target in the Banda Aceh City RAD-GRK (2020-2025), and the National targets of Near Zero Waste Emission (NZE 2050) based on the Long-term strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050. These documents provide cumulative targets rather than annual implementation rates; the annual changes used in this study were derived through linear interpolation. Specifically, assumed that the percentage of composting and recycling rates would increase by 1% each year since 2025, so the amount of waste transferred can also be reduced. Meanwhile, the rates of landfill disposal and open burning were assumed to decrease by 0.5% and 0.03% per year. This assumption is not only chosen based on existing targets but also takes into account the existing conditions of domestic waste management in Banda Aceh, with the largest waste composition being organic waste that can be composted (Praptyanti et al., 2022) and inorganic waste (such as plastic, rubber, and iron) that can still be recycled (Idawati, 2020), so that residual waste, glass, and other types of waste are only buried or transferred to regional landfills.

Based on the results of the calculation of GHG emissions using scenario 2, which assumed a decreasing in the percentage of emissions each year. In Table 5, the amount of GHG emissions in 2025 is 9,371 Gg CO_2-eq, meanwhile, in 2050, there is a decrease in emissions from the waste sector, reaching 6.935 Gg CO_2-eq. In addition, organic waste composting activities are the largest contributor to emissions up to 6.128 Gg CO_2-eq in 2050, followed by a decrease in the amount of emissions from waste disposal in landfills from 8.28 Gg CO_2-eq in 2024 to 0.8 Gg CO_2-eq in 2050, and open waste burning, namely 0.005 Gg CO_2-eq. These results align with research by Febrianti et al., (2023), which states that increasing the amount of waste composted in a region will reduce the amount of waste dumped in landfills and burned by the community. In Scenario 2, the increase in the amount of waste composted and recycled each year is the main factor influencing emissions (Romawati, 2018), even though Recovery remains zero (0).

Based on the comparison between scenarios 1 and 2, it is known that the amount of emissions generated by waste management in Banda Aceh City in 2050 will decrease, namely 40.9%, if scenario 2 is implemented. This percentage reduction is quite large and is considered ideal because it also reaches the national target based on the Enhanced Nationally Determined

Contribution (ENDC) document (Indonesia, 2022), namely a 29% reduction independent of total BaU emissions. This shows that emission reduction through increased composting and recycling can contribute directly to the amount of GHG emissions in Banda Aceh City. Therefore, interventions in the form of efforts to reduce GHG emissions from the waste management sector are proven to be very necessary.

Strategies for achieving net-zero emissions in domestic waste management are important for a sustainable society, but insights that can guide global policy-making are still scarce (Gu et al., 2025). In Indonesia, research related to determining environmental strategy recommendations using the SBSC approach is still very rare; most research related to efforts to reduce GHG emissions in the waste management sector still uses the SWOT method. SWOT method formulates the strategy in relation to four sets of considerations: Strengths, Weaknesses, Opportunities, and Threats. While strengths and weaknesses relate to the resources and capabilities of the firm, opportunities and threats relate to the external environment. Although SWOT method widely used, it mainly serves as a situational analysis tools and does not provided a structured mechanism for translating strategies into measurable objectives and performance indicator. In contrast, SBSC can integrates and shows the cause-and-effect linkages all perspectives into a coherence strategy implementation, and performance evaluation. These linkages visualize hypotheses that are based on the principle of cause and effect and on the paradigm of instrumental rationality in particular (Moller & Schaltegger, 2005)

The results of the performance analysis of the five SBSC perspectives related to waste management in Banda Aceh City, in Table 6, show that the environmental perspective and the social perspective obtained the lowest percentage of performance values, respectively, namely 55.21 with a score of 11.04 and 64.33 with a score of 12.87. The low results of the performance calculation on waste management in Banda Aceh City indicate that sustainable and environmentally friendly management activities have not been implemented (Kalender & Vayvay, 2016) As a result, it highly potential to be further optimized. Additionally, these two perspectives are also modified perspectives on the BSC, which emphasize the sustainability aspect in domestic waste management.

This has several limitations. The analysis relied on secondary data without direct sampling and did not include wastewater emission analysis. The analysis assumed constant waste composition and characteristics throughout the period. Another limitation lies in the deterministic condition of the scenario assumption. In scenario 2, the annual changes of composting, recycling, landfill disposal, and open burning waste were developed from local and national policy targets using linear interpolation between baseline and the target condition, which does not fully capture the uncertainties associated with policy implementation and real changes. Moreover, the relatively small number of experts as respondents may limit the diversity of perspectives represented in the strategic recommendations.

4. CONCLUSION

This study contributes to integrating the IPCC 2006 method to calculate the amount of GHG emissions with strategic environmental planning to be addressed within a single analytical framework by the SBSC method.

Despite assuming the same population and waste generation for both scenarios, there is a significant reduction in greenhouse gas emissions if scenario 2 is implemented. This contrasts sharply with the BaU scenario, which assumes no government intervention. It also demonstrates that increasing the percentage of composting and recycling can reduce the amount of waste disposed of in landfill and burned openly. Based on the analysis using the Balanced Scorecard method, the environmental and social sustainability perspectives should be further optimized, as they received the lowest scores.

This study has several limitations, such as data quality, uncertainty of scenario assumptions, and respondent limitations. Future research should incorporate field measurements, uncertainty analysis, and cost-benefit evaluation of the proposed mitigation strategies.

REFERENCES

Alamsyah, L. F., Firdaus, M., & Baga, L. M. (2019). Strategi Peningkatan Kinerja Menggunakan Balanced Scorecard Pada Pemerintah Kota Jakarta Utara. *Jurnal Manajemen Pembangunan Daerah*, 9(1), 17–24. https://doi.org/10.29244/jurnal_mpd.v9i1.27541

Badan Perencanaan Pembangunan Nasional. (2014). *Pedoman Teknis: Perhitungan Baseline Emisi Gas Rumah Kaca Sektor Pengelolaan Limbah*. Bappenas Republik Indonesia.

Chaerul, M., Febrianto, A., & Tomo, H. S. (2020). Peningkatan Kualitas Penghitungan Emisi Gas Rumah Kaca Dari Sektor Pengelolaan Sampah Dengan Metode IPCC 2006 (Studi Kasus: Kota Cilacap). *Jurnal Ilmu Lingkungan*, 18(1), 153–161. https://doi.org/10.14710/jil.18.1.153-161

Das, B., Bhave, P. V., Sapkota, A., & Byanju, R. M. (2018). Estimating Emissions From Open Burning of Municipal Solid Waste in Municipalities of Nepal. *Waste Management*, 79, 481–490. https://doi.org/10.1016/j.wasman.2018.08.013

DLHK Kota Banda Aceh. (2020). *Rencana Aksi Daerah Penurunan Gas Rumah Kaca (RAD GRK) 2020–2025*. Dinas Lingkungan Hidup, Kebersihan dan Keindahan Kota Banda Aceh.

Epstein, M. J., & Wisner, P. S. (2001). Using a Balanced Scorecard to Implement Sustainability. *Environmental Quality Management*, 11(2), 1–10. https://doi.org/10.1002/tqem.1300

Febrianti, N., Prambudi, D. A., & Anggraeny, R. D. (2023). Analisis Emisi Gas Rumah Kaca (GRK) Pada Pengelolaan Sampah Organik (Studi Kasus: ITF Kota Hijau Balikpapan). *Jurnal Sains & Teknologi Lingkungan*, 15(2), 106–120. https://doi.org/10.20885/jstl.vol15.iss2.art1

Figge, F., Hahn, T., Schaltegger, S., & Wagner, M. (2002). The Sustainability Balanced Scorecard – Linking Sustainability Management to Business Strategy. *Business Strategy and the Environment*, 11(5), 269–284. https://doi.org/10.1002/bse.339

Government of Indonesia. (2021). *Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050*. Ministry of Environment and Forestry.

Intergovernmental Panel on Climate Change. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

Hutagalung, W. L. C., Sakinah, A., & Rinaldi, R. (2020). Estimasi Emisi Gas Rumah Kaca Pada Pengelolaan Sampah Domestik Dengan Metode IPCC 2006 di TPA Talang Gulo Kota Jambi. *Jurnal Teknik Sipil dan Lingkungan*, 5(1), 59–68. https://doi.org/10.29244/jsil.5.1.59-68

Indawati, L. (2020). Identifikasi Timbulan Dan Emisi Gas Rumah Kaca Sampah Pasar di Kota Surabaya. *Matriks Teknik Sipil*, 8(4), 454–461. https://doi.org/10.20961/mateksi.v8i4.48966

Isya, A. A., Arman, K. R., & Wintoko, J. (2021). Mini-Review Teknologi Carbon Capture and Utilization (CCU) Berbasis Kombinasi Proses Kimia dan Bioproses. *Equilibrium Journal of Chemical Engineering*, 4(2), 71–78. https://doi.org/10.20961/equilibrium.v4i2.47908

Johannes. (2009). *Balanced Scorecard Konsep dan Implementasi*. Universitas Jambi.

Julia Lingga, L., Yuana, M., Aulia Sari, N., Nur Syahida, H., & Sitorus, C. (2024). Sampah di Indonesia: Tantangan dan Solusi Menuju Perubahan Positif. *Innovative: Journal of Social Science Research*, 4(3), 12235–12247.

Kalender, Z. T., & Vayvay, Ö. (2016). The Fifth Pillar of the Balanced Scorecard: Sustainability. *Procedia - Social and Behavioral Sciences*, 235, 76–83. https://doi.org/10.1016/j.sbspro.2016.11.027

Keller, C. F. (2009). Global Warming: A Review of This Mostly Settled Issue. *Stochastic Environmental Research and Risk Assessment*, 23(5), 643–676. https://doi.org/10.1007/s00477-008-0253-3

Kementerian Lingkungan Hidup. (2012). *Pedoman Penyelenggaraan Inventarisasi Gas Rumah Kaca: Buku II - Volume 4 Metodologi Penghitungan Tingkat Emisi Gas Rumah Kaca Pengelolaan Limbah*. Kementerian Lingkungan Hidup Republik Indonesia.

Kementerian Lingkungan Hidup dan Kehutanan. (2024). *Rencana Operasional Indonesia Zero Waste Emission 2050*. KLHK Republik Indonesia.

Lestari, J. A. (2017). *Strategi Adaptasi dan Mitigasi Penurunan Emisi Gas Rumah Kaca (GRK) Sektor Transportasi dan Sektor Persampahan di Kota Batu* [Tesis, Institut Teknologi Sepuluh Nopember]. Institutional Repository ITS.

Mohareb, E. A., MacLean, H. L., & Kennedy, C. A. (2011). Greenhouse Gas Emissions From Waste Management: Assessment of Quantification Methods. *Journal of the Air & Waste Management*

Association, 61(5), 480–493. https://doi.org/10.3155/1047-3289.61.5.480

Möller, A., & Schaltegger, S. (2005). The Sustainability Balanced Scorecard as a Framework for Eco-Efficiency Analysis. *Journal of Industrial Ecology*, 9(4), 73–83. https://doi.org/10.1162/108819805775247927

Nurfadillah. (2022). *Pemodelan Emisi Gas Rumah Kaca Pada Lahan Sawah Menggunakan Sistem Dinamik di Kabupaten Bone* [Skripsi, Universitas Hasanuddin]. Repository UNHAS.

Pemerintah Kota Banda Aceh. (2019). *Strategi Percepatan Pembangunan Sanitasi Permukiman: SSK Kota Banda Aceh 2019–2024*. Bappeda Kota Banda Aceh.

Praptyanti, D. A. U. R., Barchia, M. F., Utama, S. P., Suharyanto, & Yansen. (2022). Strategi Mitigasi Emisi Gas Rumah Kaca (GRK) Sektor Persampahan di Kabupaten Lebong (Studi Kasus Kecamatan Amen). *Naturalis: Jurnal Penelitian Pengelolaan Sumber Daya Alam dan Lingkungan*, 1(3), 29–39.

Rismawati. (2017). *Strategi Mitigasi Penurunan Emisi Gas Rumah Kaca (GRK) di Kota Jayapura* [Tesis, Universitas Hasanuddin]. Repository UNHAS.

Romawati, W. E. (2018). *Estimasi Emisi Gas Rumah Kaca Dari Sampah Rumah Tangga di Kecamatan Bulak, Kota Surabaya Dengan Metode IPCC* [Skripsi, Institut Teknologi Sepuluh Nopember]. Institutional Repository ITS. https://repository.its.ac.id/53413/

Samin, Sumartio, & Rahmat, M. (2018). Perencanaan Tempat Pemrosesan Akhir Sampah Dengan Menggunakan Metode Sanitary Landfill. *Jurnal Media Teknik Sipil*, 15(2), 117–125. https://doi.org/10.22146/jmts.v15i2.5020

Sembiring, E. T. (2021). Estimasi Mitigasi Gas Rumah Kaca Dengan Penerapan Daur Ulang Sampah (Studi Kasus: Universitas Agung Podomoro). *Architecture Innovation Journal*, 5(1), 25–42.

Tsai, F. M., Bui, T. D., Tseng, M. L., Wu, K. J., & Chiu, A. S. (2020). A Performance Assessment Approach for Integrated Solid Waste Management Using a Sustainable Balanced Scorecard Approach. *Journal of Cleaner Production*, 251, Pasal 119740. https://doi.org/10.1016/j.jclepro.2019.119740

UNICEF. (2024). *State of Global Air 2024: A Special Report on Global Exposure to Air Pollution and Its Health Impacts, With a Focus on Children's Health*. Health Effects Institute.

United Nations Environment Programme. (2010). *Waste and Climate Change: Global Trends and Strategy Framework*. UNEP.

Wargahadibrata, R., Rosehan, A., Susanti, S., Fitrina, E., Puspawardani, V., Kurniawan, A. A., Alexander, K., & Triatmojo, A. (2020). *Pedoman Penyusunan Data Aktivitas IGRK (Inventarisasi Gas Rumah Kaca) Pemerintah Daerah Sektor Limbah 2020*. Kementerian Lingkungan Hidup dan Kehutanan.

WMO. (2023). *WMO Greenhouse Gas Bulletin No. 19: The State of Greenhouse Gases in the Atmosphere Based on Global Observations Through 2022*. World Meteorological Organization.

Wulandari, A., Mulyanto, H., Anis, B. J., Hidayat, T., Riwayadi, E., Panahatan, M. B., Ikhwani, M., Suparnoh, Wibowo, A., Bayhaki, & Supriyadi, D. A. (2016). *Mutu dan Kinerja* (F. Rezeki, Ed.). PT Kimshafi Alung Cipta.

Yunitasari, A. I. (2014). *Pengelolaan Tempat Pemrosesan Akhir (TPA) Berdasarkan Prinsip Pembangunan Berkelanjutan* [Skripsi, Universitas Brawijaya]. Repository UB.