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Environmental Impact of Waste to Energy Scenario in Developing Country, Case Study of Makassar, Indonesia

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ABSTRACT

The waste management issue in developing countries, particularly in Indonesia, remains uncontrolled and is urgent to address. This problem is significantly tied to the issue of resource scarcity and global climate change. Various policies have been formulated, both globally and nationally, to resolve this issue. Makassar City is one of the cities the government should target to achieve the goal of converting waste into energy by 2025. This study focuses on the environmental impact of various scenarios on waste-to-energy potential using life cycle assessment (LCA) in Makassar City. The waste management strategy in this study uses five scenarios, comparing incinerators generating electricity, landfills with gas, and composting. The results showed that scenario 5, which has a low environmental impact, consists of 10% composting, 45% incineration, and 45% landfill gas (LFG). Incineration can reduce 45% of solid waste disposal (SWD) and produce 1.45 E + 08 kg/year of CO_2 emissions. The waste-to-energy (WtE) scenario model significantly reduces the environmental impact, especially the concentration of greenhouse gases (GHGs) in the atmosphere. The role of incinerators in the environment is not only to reduce the volume of SWD per year but also to provide a new source of energy. The LFG collector plays a crucial role in reducing the concentration of CH_4 in the atmosphere due to its facility for capturing CH_4 gas.

Keywords: environmental impact, waste to energy, developing country.

INTRODUCTION

Municipal solid waste (MSW) is a worldwide concern that continues to be an environmental and social trend in urban areas. Significant increases in population, economic growth, rapid lifestyle changes, and accelerated urbanization have driven waste generation to become uncontrollable, especially in developing countries (Bartolacci et al., 2019; Marshall and Farahbakhsh, 2013; Turner et al., 2016). Over the past decade, urban waste generation from 2000 to 2010 increased rapidly by 87.5%, from 0.64 kg/day/person to 1.2 kg/day/person (Hoornweg and Bhada-Tata, 2012). Globally, the world produces 2.01 billion tons of urban waste annually, and it is predicted that by 2050, This quantity is expected to rise to 3.4 billion tons annually (Kaza et al., 2016).

As a part of developing countries and ranked as the fourth most populous nation in the world, Indonesia generated approximately 19.56 million tons of waste in 2023. Unfortunately, MSW remains a significant issue due to conventional and environmentally unfriendly waste management practices, such as relying on open dumping methods, which are applied in most cities in Indonesia (Aprilia, 2021). Although regulations stipulate sanitary landfills, most are operated using open dumping landfill methods (Damanhuri et al., 2014). Several studies indicate that improperly managed open dumping systems lead to various types of pollution, including contamination of aquatic environments, soil, and air (Abubakar et al., 2022; Lestari and Trihadiningrum, 2019; Nurhasanah et al., 2021; Siddiqua et al., 2022).

On the other hand, the world is facing issues of resource scarcity and global climate change. This condition has driven progress in improving more integrated municipal solid waste (MSW) management. In accordance with the Sustainable Development Goals (SDGs) framework, mainly focusing on the goal of affordable and clean energy (SDG 7) among the 17 targeted goals, WtE systems have become part of renewable energy production and enable the reduction of environmental impacts in both developed and developing countries (Alao et al., 2022). WtE is considered a highly preferred option on a global scale. Previous studies have shown that several countries have implemented WtE technology for waste management, including the USA (Foster et al., 2021; Mukherjee et al., 2020), European countries (Chaliki et al., n.d.), India (Malav et al., 2020), China (Themelis and Ma, 2021), and Japan (Tabata, 2013). Mechanical grate (MG) incinerators are widely used globally for WtE implementation (Lu et al., 2017). Meanwhile, fluidized bed (FB) incinerators dominate the market in Asian countries compared to Europe due to their superior ability to process high-moisture MSW (Chen and Christensen, 2010).

Several strategies have been formulated to improve waste management through renewable energy methods, particularly in developing countries. In Indonesia, the initial regulation on solid waste management is outlined in Regulation Number 18/2008, which serves as the foundation for proper MSW management through the Reduce, Reuse, and Recycle (3R) program (Damanhuri et al., 2014). Following Presidential Regulation No. 97/2017, also known as Jakstranas, there are goals established to achieve a 30% reduction in MSW and effectively handle 70% of MSW by the year 2025 (National Plastic Waste Reduction Strategic Actions for Indonesia, n.d.). Another government program for waste management focuses on renewable energy through the utilization of WtE. This strategy is detailed in Government Regulation No. 79/2014, which targets to raise the contribution of new and renewable energy sources to 23% by 2025 (Mustafa et al., 2022). The government is increasingly focusing on incineration-based WtE plants to achieve the target of handling 70% of waste by 2025. These WtE plants are regulated under Presidential Regulation No. 35/2018, which extends coverage to twelve major cities in Java, Sulawesi, Sumatra, and Bali. The expected target is to generate up to 234 megawatts of electricity by utilizing 16.000 tons of waste per day (The Economic and Social in Indonesia).

Selecting the best WtE technology presents its challenges, as there are no definitive selection guidelines based on technical and geographical aspects (Dong et al., 2018). Hence, a comprehensive methodology is required to assess the overall environmental impact of different MSW systems. Life cycle assessment (LCA) is commonly employed as it evaluates the entire life cycle of a product or waste, from inception to disposal, encompassing waste raw materials, transportation, and final processing. Research on LCA related to WtE continues to evolve with the ongoing development of new technologies. This situation contrasts with Indonesia, where studies on the environmental impact of WtE are still limited. For example, research on the potential for energy recovery from MSW in Semarang (Lokahita et al., 2019), the potential of LFG in Balikpapan city (Banaget et al., 2020), and the potential and environmental impact of WtE incinerators on the island of Java (Zeng et al., 2024).

In Indonesia, one of the major cities targeted by the government for the WtE program is Makassar, located in the eastern region of Indonesia (Sulawesi Island). The waste potential of Makassar currently reaches 1.139 tons per day (Muis et al., 2023), with a composition dominated by 55% organic waste and 45% non-organic waste (Muis et al., 2024). Currently, waste management in Makassar still relies on landfills with an open dumping system as the final waste destination, exacerbated by landfills exceeding their capacity. Therefore, it is urgent for Indonesia, especially Makassar, to address the issue of waste pollution. The focus of this study is to integrate policy directives related to MSW and energy in Indonesia, considering environmental and energy aspects. This study presents the potential WtE scenarios in Makassar, Indonesia, and uses the LCA method to interpret the environmental impact assessment.

MATERIALS AND METHODS

Location of study

This study was carried out in Makassar City, situated on the island of Sulawesi in Indonesia. Figure 1 illustrates the map of Indonesia, with an

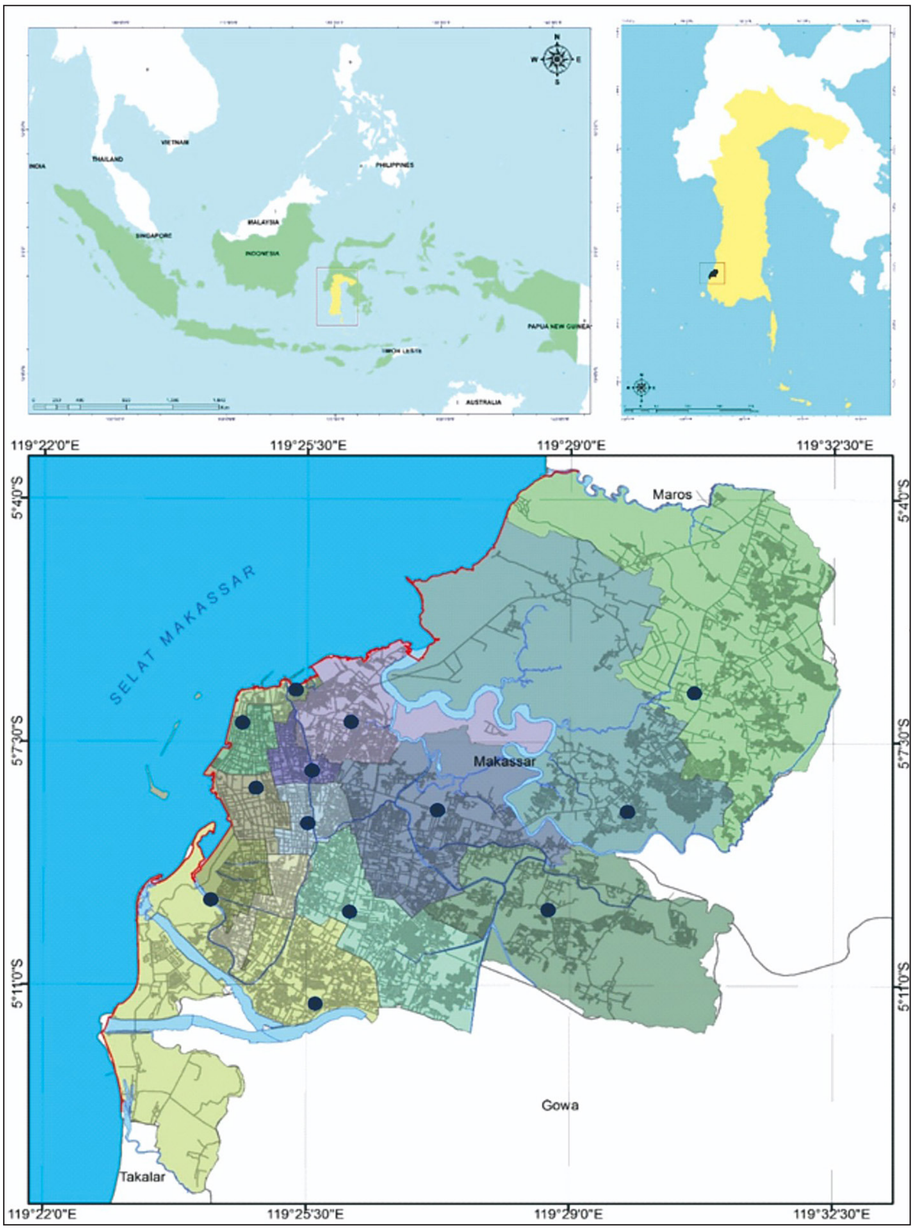

Figure 1. Location of study

arrow pointing to Sulawesi Island and then to the study area. Geographically, Makassar City is located between 5°08'6.19'' S and 119°24'17.38'' E. As the fourth largest city in Indonesia in 2022, Makassar had a population of 1,432,189 residents. Makassar City covers an area of 175.77 km² and is administratively divided into 14 districts and 143 villages (Amukti et al., 2020). The average elevation of Makassar City ranges from 2 meters to 22 meters above sea level.

Life cycle analysis

Life cycle assessment is a method employed to evaluate potential environmental impacts by quantifying the emissions associated with different MSW management practices, starting from waste sources, transportation, processing, and disposal of various fractions and residues. This LCA study is conducted following the 2006 ISO 14040 and 14044 standards. The LCA study comprises four phases: Goal and Scope Definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (Zegardło, 2021).

Goal and scope

The LCA study aims to obtain appropriate model scenarios based on the environmental impacts of various WtE treatments, including composting, incineration, and LFG methods. The system boundary in this study (Figure 2) begins with the collection and transportation of MSW from its source to the treatment facility. It is assumed that Waste Banks and scavengers reduce 3R waste. The study consists of five handling scenarios named scenarios 1, 2, 3, 4, and 5, in addition to the business-as-usual (BaU) scenario. The approach to scenario development includes the current waste management conditions in Makassar City, which still employs an Open Dumping system. Furthermore, several regulations on MSWM are considered, including the National Policy and Strategy (Jastranas) for Household Waste Management and Household Waste Types (Presidential Regulation of the Republic of Indonesia Number 97 of 2017), Presidential Regulation Number 35 of 2018 on Environmentally Friendly Waste-to-Energy Plant Development, and the Regional Policy and Strategy (Jastrada) on Household Waste Management and Household Waste Types (Mayor Regulation Number 36 of 2018).

Figure 2 illustrates the System Boundary of the LCA Study from MSW transportation to the sorting facility and the preparation site according to the scenario. Inputs include water, fuel, and electricity. The outputs consist of air emissions, water emissions, soil emissions, by-products such as electricity, and materials from the processing residues. The impact categories were selected for the Waste-to-Energy scenarios: Global warming potential (GWP) is based on emissions of CO_2, CH_4, and N_2O.

Scenarios

Five different scenarios are compared in this study. The first scenario considers the current waste management situation in Makassar, while the other five scenarios represent the national government targets for waste treatment with WtE technology. The various scenarios in Table 1 is briefly explained here.

BaU (Business as Usual):

The baseline scenario represents the existing solid waste management condition in Makassar. In this baseline scenario, the process includes 5% composting and 95% landfill without energy recovery:

- Scenario 1: in Scenario 1, waste treatment allocation favors incineration over landfill gas recovery. It is assumed that the allocation for composting is 10%, incineration is 60%, and landfill gas is 30%.
- Scenario 2: in scenario 2, waste processing combines incinerator technology and landfill gas. The assumption is that more waste is processed for LFG recovery, with a value of 60%, compared to incineration with 30%, and composting process with 10%.
- Scenario 3: in Scenario 3, the waste treatment allocation focuses more on incineration with 85% and composting with 15%. There is no waste treatment using landfill gas in this scenario.
- Scenario 4: in Scenario 4, the waste treatment allocation focuses more on landfill gas

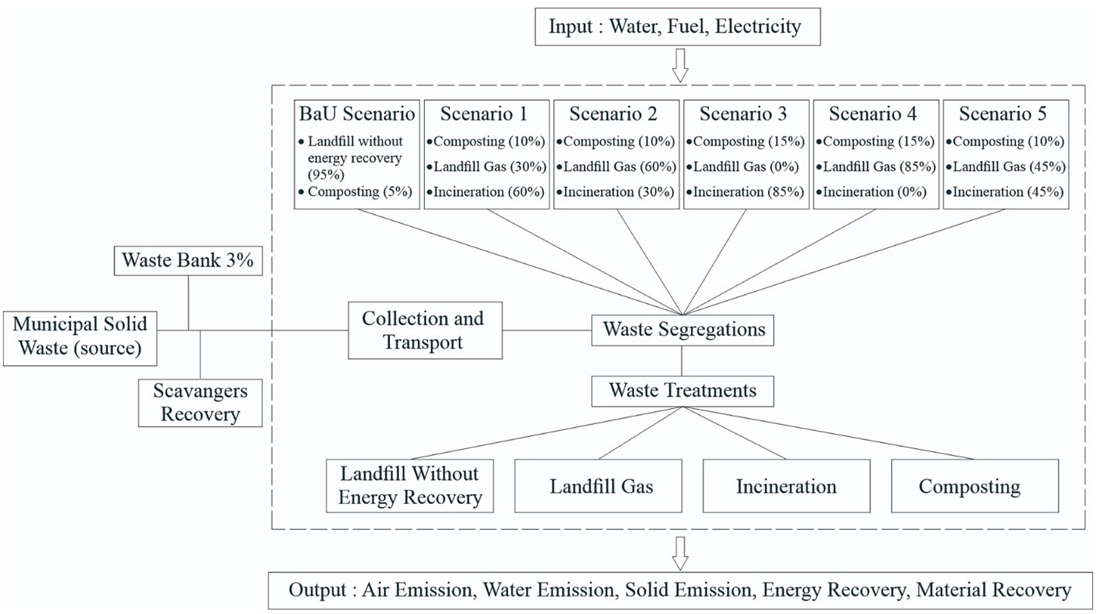

Figure 2. System boundary

Table 1. Scenario of waste allocation for waste to energy (WtE) in Makassar 2025

Treatment	BaU	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Landfill without energy recovery	95%	0%	0%	0%	0%	0%
Composting	5%	10%	10%	15%	15%	10%
Incineration	0%	60%	30%	85%	0%	45%
Landfill gas	0%	30%	60%	0%	85%	45%

recovery with 85% and composting with 15%. There is no waste treatment using incineration in this scenario.

- Scenario 5: Scenario 5 assumes an equal allocation for incineration and landfill gas recovery. The scenario includes 10% composting, 45% incineration, and 45% landfill gas recovery.

Life cycle inventory

Waste composition

Makassar is categorized as a major city with a population of 1.432.189 in 2022 (Makassar Bureau of Statistics, 2023). Various waste generation surveys show that the average waste generation rate is 0.62 kg/day. Figure 3 offers an overview of the composition of waste in Makassar, showing that bio-waste accounts for 54.7%, wood 11.33%, plastic 8.8%, paper 6.78%, PET plastic bottles 3.40%, cans 1.30%, metal 1.07%, glass 1.15%, batteries 0.62%, rubber 0.42%, and other unidentified waste 10.36%. Based on the waste composition, bio-waste, which includes compostable waste such as food scraps, accounts for 54.74% of the total waste. The waste composition is used to determine the quantity and type of solid waste in each processing stage using WtE technology.

Collection and transport

The waste collection pattern in Makassar City has utilized a door-to-door system. This direct collection system involves simultaneous waste collection and transportation. The waste transportation of MSW in Makassar City covers a total route length of 12,536.7 kilometers annually (Figure 4, Table 2). There are 319 trucks in operation, distributed across 15 districts. Each truck consumes 15 liters of diesel daily, and each car has a capacity of 2.5 tons. The diesel consumption rate for these trucks is 0.53 liters per kilometer, which means an average of 5.5 liters per ton of waste transported. This rate highlights the importance of optimizing route efficiency and maintaining truck conditions to minimize fuel consumption and emissions. The daily diesel consumption for waste transportation reaches 4.774 liters.

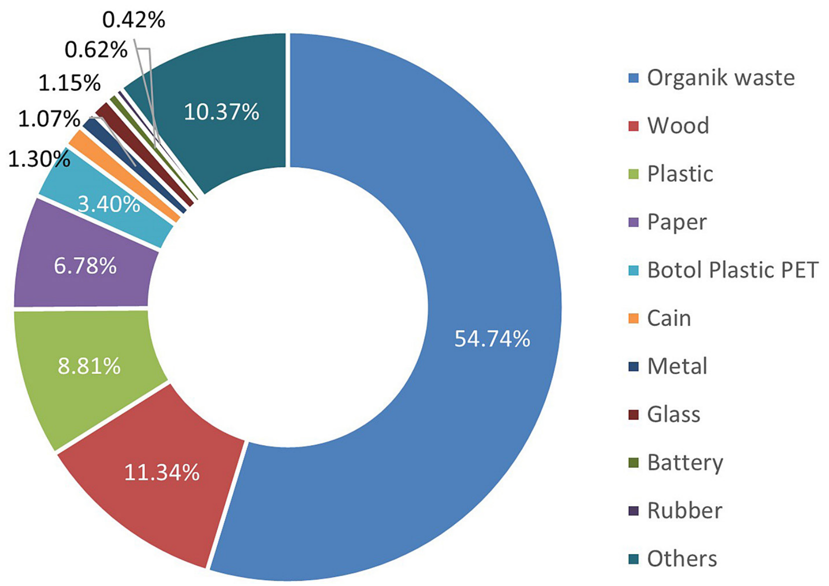

Figure 3. Waste composition

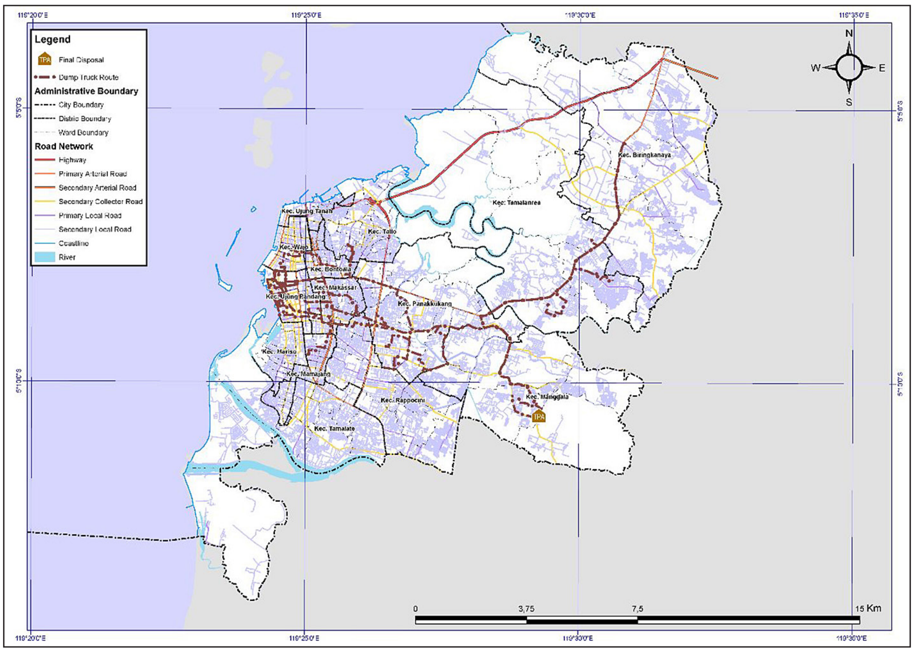

Figure 4. Transport route

Table 2. Inventory data of waste transportation

Waste transportation distance	km	12,536.7
Truck	unit	319
Truck capacity	ton/truck	2.5
Diesel consumption	liter/unit/day	15
Diesel consumption rate	liter/km	0.53
Total daily diesel consumption	liters/day	4774

Landfill

Solid waste disposal site (SWDS) Tamangapa is located 15 km from the centre of Makassar City. It lacks a cover layer of soil, membrane, and vegetation, with a wavy surface and pile heights reaching up to 20 meters. The functional unit for calculating GHG emissions at a landfill without energy recovery is the amount of MSW per year (Mustafa et al., 2022). For the landfill and excavation processes, eight units of Komatsu PC 210 standard excavators from the year 2022 are used, working alternately for 24 hours per day with a total fuel requirement of 1200 liters per day (Figure 5).

Landfilling activities generate two primary greenhouse gas components: CO_2 and CH_4 (Yang et al., 2013). Additionally, they produce small amounts of Nitrous Oxide (N_2O), Nitrogen Oxide (NO_X), and Carbon Monoxide (CO) (Table 3), (IPCC, 2006). The calculation of CH_4 and CO_2 emissions is performed using the standard emission calculation formulas from IPCC 2006 with the following Equation (CH_4 emissions (Gg/yr)):

$$(MSWT \times MSWF \times MCF \times DOC \times DOCF \times \times F \times 16/12 - R) \times (1 - OX) \quad (1)$$

where: *MSWT* – total MSW produced (Gg/yr), *MSWF* – the portion of domestic waste disposed to landfill, *MCF* – methane correction coefficient, *DOC* – degradable organic carbon (kg C/kg SW), *DOCF* – Fraction DOC dissimilated, *F* – Percentage of methane in landfill gas (IPCC default is 0.5), 6/12 – conversion of C to CH_4, *R* – Recovered CH_4 (Gg/yr.), *OX* – oxidation factor (fraction – IPCC default is 0).

Composting

The degradation process of solid waste containing organic carbon (DOC) that produces CO_2 under aerobic conditions is called composting

Figure 5. Landfill activity

Table 3. Emission factors for CH_4 and N_2O emissions from biological treatment of waste

Type of biological treatment	Default emission factors for methane (CH_4) and nitrous oxide (N_2O) emissions from biological waste treatment				
	Emission factors of methane (gCH_4/kg waste treated)		Emission factors of nitrous oxide (gN_2O /kg waste treated)		Remarks
	On a dry matter basis	On a dry matter basis	On a dry matter basis	On a dry matter basis	Assumptions regarding the waste treated include 25–50% degradable organic carbon (DOC) in dry matter, 2% nitrogen (N) in dry matter, and a moisture content of 60%. The emission factors for dry waste are derived from those for wet waste, assuming a 60% moisture content in the wet waste.
Composting	10 (0.08–20)	4 (0.03–8)	0.6 (0.2–1.6)	0.24 (0.06–0.6)	
Anaerobic digestion	2	0.8	Assumed insignificant	Assumed insignificant	

Note: Source: IPCC 2006.

(IPCC, 2006). Composting is an alternative technology for reducing organic waste disposed of in landfills and recovering methane gas (Syafrudin et al., 2020). However, the methane gas produced from the composting process impacts global warming 23 times more than carbon dioxide (Yong et al., 2015). Other emissions produced include N_2O, ranging from 0.5% to 5%. The formulas used to calculate CH_4 and N_2O emissions from the composting process are as follows:

$$CH_4\ Emissions\ (Gg/year) = \Sigma i\ (Mw \times EF) \times 10^{-3} - R \quad (2)$$

where: CH_4 *Emissions* – total methane emissions in inventory year, (Gg/year), *Mw* – amount of organic waste processed through biological treatment type i, (Gg), *EF* – emission factor for waste treated type i, (g CH_4/kg), *R* – total amount of methane recovered in inventory year, (Gg).

$$N_2O\ Emissions\ (Gg/year) = \Sigma i\ (Mw \times EF) \times 10^{-3} \quad (3)$$

where: N_2O *Emissions* – total N_2O emissions in inventory year, (Gg/year), *Mw* – amount of organic waste processed by biological treatment type i(Gg), *EF* – emission factor for treatment, g N_2O /kg, *R* – total amount of N_2O recovered in inventory year, (Gg).

Incinerator

Incineration is burning solid and liquid waste in a controlled facility. To achieve more complete combustion, this method includes the input of air, extended residence time, more efficient mixing systems, and high temperatures. Like other waste-burning processes, incineration and open burning generate CO_2, CH_4, and N_2O emissions, with CO_2 emissions being more significant than those of CH_4 and N_2O (IPCC, 2006). Early-generation incinerators include metal conical, waste heat recovery, ram-feed, batch feed, and continuous incinerators. Next-generation incinerators use periodic waste combustion systems, allowing for more complete waste burning with larger capacities (Makarichi et al., 2019). More advanced incinerator technologies sort waste based on its optical properties using optical devices. One type of incinerator capable of burning large amounts of waste without sorting and shredding, except for household waste and hazardous materials, is the Moving Grate Incinerator (Wissing et al., 2017). Emissions of CO_2 and N_2O resulting from the incineration process can be computed using the formula below:

$$CO_2\ emissions\ (Gg/yr) = \Sigma i\ (SWa \times dma \times CFa \times FCFa \times OFa) \times 44/12 \quad (4)$$

where: CO_2 *Emissions* – CO_2 emissions in inventory year (Gg/yr), *SWa* – total amount of solid waste (wet weight) (Gg/yr), *dma* – dry matter content in the waste incinerated (wet weight), *CFa* – percentage of carbon in the dry matter (total carbon content), *FCFa* – percentage of fossil carbon in the total carbon, (fraction), *OFa* – oxidation factor, (fraction), 44/12 is conversion factor from C to CO_2.

$$N_2O\ emissions\ (Gg/yr) = \Sigma c\ (IWc \times EFc) \times 10^{-6} \quad (5)$$

where: N_2O *Emissions* – N_2O emissions in inventory year, Gg/yr, *IWc* – amount of incinerated waste, Gg/yr, *EFc* – nitrous oxide emission rate (kg N_2O/Gg of waste), *c,* 10^{-6} – conversion from kilogram to gigagram, *c* – category or type of waste incinerated.

Table 4 shows the paper and wood have high DOC values when dry, with the highest carbon content found in plastic waste when dry, followed by rubber.

Landfill gas

Landfill gas primarily consists of methane and carbon dioxide, alongside minor amounts of non-methane organic compounds. Efficient management and utilization of landfill gas can substantially decrease greenhouse gas emissions and offer a renewable energy source (Un, 2023). The efficiency of gas collectors in landfill systems is crucial for minimizing methane emissions and harnessing the potential of LFG as an energy resource. Proper design and maintenance of landfill gas collectors are essential to optimize gas recovery and minimize the release of methane into the atmosphere (Cudjoe and Acquah, 2021). CH_4 emissions from the landfill gas process can be calculated using the following formula:

$$CH_4 = DDOCm \times F \times 16/12 \quad (6)$$

where: CH_4 – the quantity of methane produced from biodegradable material, *DDOCm* – DDOCm biodegradable material in year, *F* – the proportion of methane, by volume, in landfill gas generated, 16/12 – molecular weight ratio CH4/C (ratio).

$$DDOCm = W \times DOC \times DOCf \times MCF \quad (7)$$

Table 4. Standard values for dry matter, DOC, total carbon, and fossil carbon fraction of different municipal solid waste (MSW) components

Types of MSW	Dry matter content of wet weight (%)	DOC wet waste (%)		DOC dry waste (%)		Total carbon content (dry weight)		Fossil carbon fraction of total carbon (%)	
	Default	Default	Range	Default	Range	Default	Range	Default	Range
Paper	90	40	36–45	44	40–50	46	42–50	1	0–5
Textile	80	24	20–40	30	25–50	50	25–50	20	0–50
Food waste	40	15	8–20	38	20–50	38	20–50	–	–
Wood	85	43	39–46	50	46–54	50	46–54	–	–
Garden waste	40	20	18–22	49	45–55	46	45–55	0	0
Nappies	40	24	18–32	60	44–80	70	54–90	10	10
Rubber and leather	84	(39)	(39)	(47)	(47)	67	67	20	20
Plastics	100	–	–	–	46–54	75	67–85	100	95–100
Metal	100	–	–	–	25–50	NA	NA	NA	NA
Glass	100	–	–	–	20–50	NA	NA	NA	NA
Other, inert waste	90	–	–	–	46–54	3	0–5	100	50–100

Source: IPCC 2006.

where: *DDOCm* – the amount of decomposable dissolved organic carbon deposited, *W* – the quantity of waste deposited (Gg), *DOC* – proportion of degradable organic carbon at the time of deposition, Gg C/Gg, DOC_f – proportion of dissolved organic carbon capable of decomposition, *MCF* – correction factor for CH_4 during aerobic decomposition at the time of deposition (Table 4).

RESULT AND DISCUSSION

Based on the Jakstranas 2025 waste management policy, LCA modeling is utilized to evaluate the environmental impacts of waste-to-energy scenarios in Makassar City. Table 5 shows the environmental impact of the current situation (BaU scenario) regarding waste transportation routes and the use of heavy equipment in landfill activities. The year 2025 is used as a baseline with waste generation amounting to 440.955.135,34 kg per year. For the landfill and excavation processes, eight units of Komatsu PC 210 standard excavators from the year 2022 are used, working alternately for 24 hours per day with a total fuel requirement of 1200 Liter per day (Makassar Government, 2022). Table 6 presents CH_4 emissions in landfills with the open dumping method that is still currently used. Regarding the mass (kg) of impacts, it was discovered that GWP100 substantially contributes to environmental impacts, particularly in scenarios where final waste disposal without energy recovery is predominant.

Based on Table 7, the direct release of CH_4 gas into the atmosphere without gas capture is 1,376.15 Gg/year (1,376.150 kg/year). Meanwhile, CH_4 emissions from composting are 88,191.02 kg/year, and N_2O emissions are 5,291.46 kg/year.. The estimation of CO_2 emissions from waste incineration can be seen in Table 8. The calculation results show that in scenario 1, incineration reduces the

Table 5. CO_2 emissions from transportation and excavation activities

SWDS activity	MSW (kg)	Distance (km)	Fuel (Liter)	EF Transport $kgCO_2$/km/ tonMSW	EF HE g/L	CO_2 kg/year
Waste transportation	418.907.378,56	4.347.152.041,75		0,0191		83.030.603,99
Heavy equipment	418.907.378,56		573.846		3.018,88	1.732.371,37

Table 6. Emission CH_4 di tamangapa landfill

MSW Component	Percentage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH4 generated Gg CH4/year
Organic waste	54.70%	229.142.335,903	15%	1.968,98	1.181,39
Wood	11.33%	47.462.205,956	43%	242.16	145.297
Plastic	8.80%	36.863.849,286			
Paper	6.78%	28.401.920,245	40%	80.67	48.400
Pet bottle	3.40%	14.242.850,861			
Textile	1.30%	5.445.795,917	24%	1.78	1.068
Metal	1.07%	4.482.308,947			
Glass	1.15%	4.817.434,850			
Battery	0.62%	2.597.225,745			
Rubber	0.42%	1.759.410,989			
Others	10.36%	43.398.804,387			
Total			1.376,15		

Table 7. CH_4 and N_2O Emissions from composting processes

Mw (Gg/year)	EF CH_4 (g CH_4/kg waste treated)	EF N_2O (g CH_4/kg waste treated)	CH_4 emissions (kg/year)	N_2O emissions (kg/year)
22.04	4	0.24	88.191,02	5.291,46

Table 8. Estimation of CO_2 emissions from waste ıncineration

Input	S1		S2		S3		S5	
Type of MSW:	Amount of waste incinerated Gg waste/year)	CO_2 emissions (Gg CO_2/year)	Amount of waste incinerated Gg waste/year)	CO_2 Emissions (Gg CO_2/year)	Amount of waste incinerated Gg waste/year)	CO_2 Emissions (Gg CO_2/year)	Amount of waste incinerated Gg waste/year)	CO_2 Emissions (Gg CO_2/year)
Organic	144.72	80.65	72.361	40.329	205.02	114.27	108.54	60.49
Wood	29.97	46.71	14.988	23.356	42.47	66.18	22.48	35.03
Plastic	23.28	64.02	11.641	32.013	32.98	90.70	17.46	48.02
Paper	17.93	0.27	8.969	0.136	25.41	0.39	13.45	0.20
Textile	3.43	1.00	1.720	0.504	4.87	6.96	2.58	0.76
Total	219.35	192.67	109.679	96.339	310.756	278.497	164.51	144.50

mass of MSW by 219.357 Gg of solid waste per year. However, this combustion activity results in CO_2 emissions from the incinerator amounting to 192.67 Gg/year (192,678.737 kg/year). CO_2 emissions from the incineration process in scenario 2 amount to 96.339 Gg/year. The highest CO_2 emissions are produced by the incinerator activity in scenario 3, amounting to 278.497 Gg CO_2/year, as this scenario involves the most extensive waste burning compared to the other scenarios. Scenario 4 has no CO_2 emissions from waste incineration because scenario 4 does not include any incineration process. The amount of CO_2 emissions in scenario 5, being the lowest due to only a portion of the total MSW being burned, is 144.509 Gg CO_2/year. CH_4 emissions from the incineration process in scenarios 1, 2, 3, and 5 are shown in Table 9. Scenario 3 produces the highest CH_4 emissions,

Table 9. Estimation of CH_4 emissions from incineration

Input	S1		S2		S3		S5	
Type of MSW:	Amount of waste incinerated Gg waste/year)	CH_4 emissions (Gg CH_4 year)	Amount of waste incinerated Gg waste/year)	CH_4 emissions (Gg CH_4 year)	Amount of waste incinerated Gg waste/year)	CH_4 emissions (Gg CH_4 year)	Amount of waste incinerated Gg waste/year)	CH_4 emissions (Gg CH_4 year)
Organic	144.72	2.894E-05	72.361	1.4472E-05	205.02	4.100E-05	108.54	2.171E-05
Wood	29.97	5.995E-06	14.988	2.9976E-06	42.47	8.493E-06	22.48	4.496E-06
Plastic	23.28	4.656E-06	11.641	2.3282E-06	32.98	6.597E-06	17.46	3.492E-06
Paper	17.93	3.588E-06	8.969	1.7938E-06	25.41	5.082E-06	13.45	2.691E-06
Textile	3.43	6.879E-07	1.720	3.4394E-07	4.87	9.745E-07	2.58	5.159E-07
Total	219.35	4.387E-05	109.679	2.1936E-05	310.756	6.215E-05	164.51	3.29E-05

Table 10. Estimation of N_2O emissions from incineration

Input	S1		S2		S3		S5	
Type of MSW:	Amount of waste incinerated Gg waste/year)	N_2O emissions (Gg N_2O year)	Amount of waste incinerated Gg waste/year)	N_2O emissions (Gg N_2O year)	Amount of waste incinerated Gg waste/year)	N_2O emissions (Gg N_2O year)	Amount of waste incinerated Gg waste/year)	N_2O emissions (Gg N_2O year)
Organic	144.72	7.24E-03	72.361	3.62E-03	205.02	1.03E-02	108.54	5.43E-03
Wood	29.97	1.50E-03	14.988	7.49E-04	42.47	2.12E-03	22.48	1.12E-03
Plastic	23.28	1.16E-03	11.641	5.82E-04	32.98	1.65E-03	17.46	8.73E-04
Paper	17.93	8.97E-04	8.969	4.48E-04	25.41	1.27E-03	13.45	1.27E-03
Textile	3.43	1.72E-04	1.720	8.60E-05	4.87	2.44E-04	2.58	2.44E-04
Total	219.35	1.10E-02	109.67	5.48E-03	310.75	1.55E-02	164.51	8.94E-03

amounting to 6.215E-05 Gg CH_4/year or 62,141 kg CH_4/year. The lowest CH_4 emissions are produced in scenario 2, with 2.1936E-05 Gg CH_4/year or 21,936 kg CH_4/year. Table 10 shows the N_2O emissions generated from the waste incineration process in all scenarios except scenario 4. The highest N_2O emissions are in scenario 3, amounting to 1.55E-02 Gg/year (15.537 kg/year). The lowest N_2O emissions are in scenario 2, amounting to 5.48E-03 Gg/year (5,483.93 kg/year). The methane emissions that cannot be captured by the gas collection facility are released into the atmosphere. Based on the calculations in Table 11, scenario 4 has the highest estimated CH_4 capture, amounting to 685.28 Gg CH_4/year, as most of the waste is processed through landfill gas in this scenario. On the other hand, the landfill gas process also releases a certain amount of CH_4 into the atmosphere. Table 12 shows that the highest amount of CH_4 emissions released into the atmosphere is in scenario 3, with 297.90 Gg CH_4/year. The following scenarios are scenario 2, scenario

Table 11. Estimation of CH_4 capture from landfill gas

MSW component	S1		S2		S4		S5	
	Amount waste (kg/year)	LFG collection (Gg CH_4/year) moderate71%	Amount waste (kg/year)	LFG Collection (Gg CH_4/year) moderate71%	Amount waste (kg/year)	LFG collection (Gg CH_4/year) moderate71%	Amount Waste (kg/year)	LFG collection (Gg CH_4/year) moderate71%
Organic waste	72.360.737,65	83.646	144.721.475,30	334.58	205.022.090,018	671.494	108.541.106,480	188.204
Wood	14.988.065,03	10.287	14.988.065,03	10.28	14.988.065,039	10.287	14.988.065,039	10.287
Plastic	11.641.215,56		11.641.215,56		11.641.215,564		11.641.215,564	
Paper	8.969.027,44	3.427	8.969.027,44	3.42	8.969.027,446	3.427	8.969.027,446	3.427
Pet bottle	4.497.742,37		4.497.742,37		4.497.742,377		4.497.742,377	
Textile	1.719.725,02	0.076	1.719.725,02	0.07	1.719.725,027	0.076	1.719.725,027	0.076
Metal	1.415.465,98		1.415.465,98		1.415.465,983		1.415.465,983	
Glass	1.521.295,21		1.521.295,21		1.521.295,216		1.521.295,216	
Battery	820.176,55		820.176,55		820.176,551		820.176,551	
Rubber	555.603,47		555.603,47	0.00	555.603,470	0.000	555.603,470	
Others	13.704.885,59		13.704.885,59		13.704.885,596		13.704.885,596	
Total		97.436		348.375		685.284	39,798	201.994

Table 12. Estimation of CH_4 emissions from landfill gas

MSW component	S1		S2		S4		S5	
	Amount waste (kg/year)	Emission (Gg CH_4/ year)	Amount Waste (kg/year)	Emission (Gg CH_4/ year)	Amount waste (kg/ year)	Emission (Gg CH_4/ year)	Amount waste (kg/year)	Emission (Gg CH_4/ year)
Organic waste	72.360.737,65	34.165	144.721.475,30	136.66	205.022.090,018	274.272	108.541.106,480	76.872
Wood	14.988.065,03	4.202	14.988.065,03	4.20	14.988.065,039	4.202	14.988.065,039	4.202
Plastic	11.641.215,56		11.641.215,56		11.641.215,564		11.641.215,564	
Paper	8.969.027,44	1.400	8.969.027,44	1.40	8.969.027,446	1.400	8.969.027,446	1.400
Pet bottle	4.497.742,37		4.497.742,37		4.497.742,377		4.497.742,377	
Textile	1.719.725,02	0.031	1.719.725,02	0.03	1.719.725,027	0.031	1.719.725,027	0.031
Metal	1.415.465,98		1.415.465,98		1.415.465,983		1.415.465,983	
Glass	1.521.295,21		1.521.295,21		1.521.295,216		1.521.295,216	
Battery	820.176,55		820.176,55		820.176,551		820.176,551	
Rubber	555.603,47		555.603,47	0.00	555.603,470	0.000	555.603,470	
Others	13.704.885,59		13.704.885,59		13.704.885,596		13.704.885,596	
Total		97.436		142.29		279.90	39.798	82.50

Note: From composting process, Table 13 shows CH_4 and N_2O emissions are produced in small amounts, specifically 0.1764 Gg CH_4/year and 0.01058 Gg N_2O/year in scenario 1, 2, and 5. In scenario 3 and 4, CH_4 and N_2O emissions are produced 0.264 Gg CH_4/year and 0.01587 Gg N_2O/year.

Table 13. Estimation of CH_4 and N_2O emissions from composting

Scenario	Mi (Gg/year)	EF CH_4 (g CH_4/kg waste treated)	EF N_2O (g CH_4/kg waste treated)	CH_4 emissions (Gg/year)	N_2O emissions (Gg/year)
1	44.096	4	0.24	0.1764	0.01058
2	44.096	4	0.24	0.1764	0.01058
3	66.143	4	0.24	0.2646	0.01587
4	66.143	4	0.24	0.2646	0.01587
5	44.096	4	0.24	0.1764	0.01058

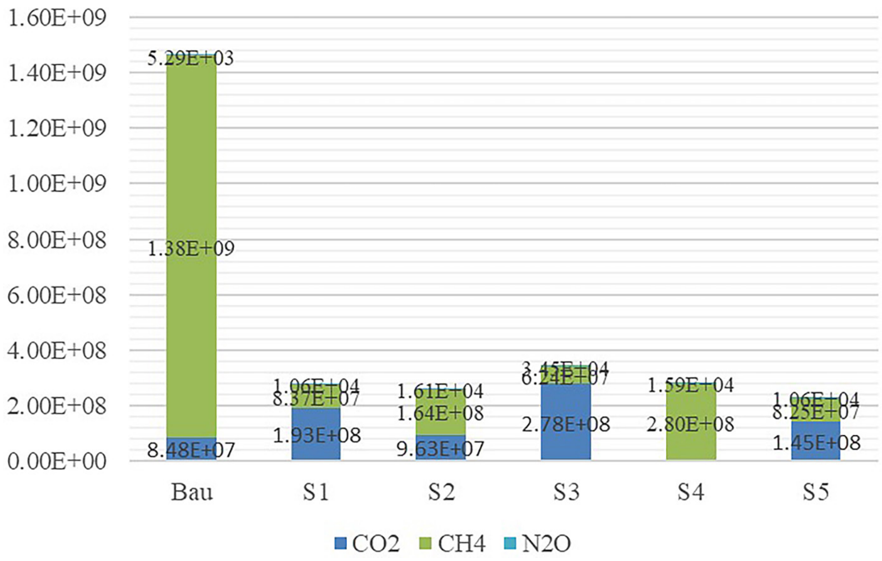

Figure 6. Life cycle environmental impact of WtE scenarios in 2025

1, and the scenario with the least emissions, scenario 4, releasing 82.50 Gg CH_4/year.

Environmental impact of all scenarios

The open dumping and landfilling activities at the Makassar landfill result in significant emissions of CO_2, CH_4, and N_2O (8.48 E+07 kg CO_2/year, 1.38 E+09 kg CH_4/year, and 5.29 E+03 kg N_2O/year). These gases are classified as greenhouse gases (GHGs) and contribute to global warming. On the other hand, there is potential energy that can be generated if CO_2, CH_4, and N_2O emissions are recovered.

Figure 6 shows that scenario 5 has a low environmental impact, consisting of 10% composting, 45% incineration, and 45% LFG. Incineration can reduce 45% of SWD and produce 1.45E+08 kg/year of CO_2 emissions. The recovered CO_2 is then used for heating. The heat is used to boil water, the steam of which is used to turn turbines (PLTSa). The captured CH_4, 8.25 E+07, is recovered and turned into synthetic gas (Syngas), which can also be used for electricity generation or as room heating.

Scenarios 1 and 4 tend to have similar values but with different types of emissions. Scenario 3 is dominated by CO_2 emissions due to incinerator activities (burning 85% of SWD/year). Meanwhile, scenario 4 is dominated by CH_4 gas that cannot be contained by the LFG collector.

CONCLUSIONS

Environmental impact of Waste to Energy scenario in Makassar, found Scenario 5, with a low environmental impact, consists of 10% composting, 45% incineration, and 45% LFG. Incineration can reduce 45% of SWD and produce 1.45 E+08 kg/year of CO_2 emissions. The WtE scenario model significantly reduces the environmental impact, especially the concentration of GHGs in the atmosphere. The role of incinerators in the environment is not only to reduce the volume of SWD per year but also to provide a new source of energy. The LFG collector is essential for decreasing atmospheric CH_4 concentrations by effectively capturing methane gas.

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