Assessment of Waste Management and Energy Recovery Scenario in Developing Country: Case Study of Makassar, Indonesia

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Chapter 1 Introduction

1.1.Background

In an era characterized by rapid urbanization and industrialization, developing countries are increasingly confronted with the dual challenges of effective waste management and sustainable energy production. The traditional practice of waste disposal in landfills not only consumes valuable land resources but also poses significant environmental and public health risks. Landfills are notorious for generating greenhouse gases like methane, contributing to global climate change, and leachate, which can contaminate soil and water sources. Simultaneously, the global demand for renewable energy sources is intensifying as nations strive to mitigate climate change impacts and reduce dependency on fossil fuels. This confluence of challenges and opportunities forms the basis for exploring innovative solutions that can transform waste into a valuable resource, thereby addressing waste management issues while contributing to energy sustainability.

The increasing volume of municipal solid waste (MSW) generated in developing countries like Indonesia necessitates urgent and innovative waste management solutions. Traditional methods such as open dumping and basic landfill operations are no longer viable due to their adverse environmental impacts and the growing scarcity of land. Moreover, the increasing awareness of the need for sustainable development has prompted the exploration of alternative waste management strategies that not only mitigate environmental harm but also harness waste as a resource.

Reviewing the government policy in Law Number 18 of 2008 on Waste Management in Indonesia reveals the need for a fundamental paradigm shift in waste management. It calls for a change from the old paradigm of collect – transport – dispose to a management approach that emphasizes waste reduction and treatment. Participation from the government, businesses, and the wider community is necessary to carry out activities aimed at reducing waste generation, recycling, and reusing waste, known as Reduce, Reuse, and Recycle (3R) (KLH, 2013). The government has set targets for cities in Indonesia in the form of the National Strategy Policy on Waste Management, which aims for 30% reduction and 70% treatment of waste by 2025 (KLHK, 2018).

Makassar, a metropolitan city in Indonesia, serves as the focal point of this study. With a population of approximately 1.43 million people and an annual growth rate of 2.8% (2018-2022), Makassar epitomizes the urban centers in developing nations that face burgeoning waste management challenges. The city's current waste management practices predominantly involve landfilling, a method that is increasingly proving unsustainable given the city's growth and environmental constraints.

Makassar, with its extensive urban sprawl and rising population, is an exemplary case for examining the potential of WtE technologies. The city's waste composition, which includes a significant proportion of organic matter, plastics, and other combustible materials, is suitable for various WtE processes such as incineration, anaerobic digestion, and gasification. These technologies can convert waste into energy in the form of electricity, heat, or fuel, thus providing a dual benefit of waste reduction and energy production.

1.2. Objectives and Scopes

1.2.1. Research Objectives

Makassar, as the largest city in Eastern Indonesia and the seventh largest city in Indonesia, has a strategic position as it is located at the crossroads of traffic routes from the south and north within the province of Sulawesi, from the Western region to the Eastern region of Indonesia, and from the northern to the southern regions of Indonesia. However, up to now, Makassar still faces environmental issues, particularly in municipal solid waste (MSW) management. Makassar has become one of the government's targets in the implementation of Waste to Energy (WtE), which can be a solution for improving waste management. This study has the following main objectives:

a. Reviewing the importance of Waste to Energy in developing countries

b. Analyzing of current waste management system in Makassar
c. Investigating the potential of landfill waste through landfill mining in Makassar City
d. To conduct an environmental risk assessment of waste management scenarios in terms of biological waste treatment
e. To conduct an environmental risk assessment of Waste to Energy scenario in Makassar.

The data for this study were collected through data retrieval from the Makassar City Government, such as the Regional Environmental Agency, the Tamangapa Makassar Landfill Unit Office, the Regional Development Planning Agency, the Cleansing Agency, the Public Works Agency, and the Central Statistics Agency of Indonesia. Additional data were obtained through field observations and interviews. Data collection for this research was conducted in Makassar City from September 2022 to May 2023.

1.3. Methodological Framework

Several research stages were conducted to achieve the research objectives. First, a literature review on waste to energy was carried out from the perspective of developing countries. The literature review used bibliometric analysis and qualitative content analysis. The second stage involved reviewing the current waste management system in Makassar City. This chapter describes the existing condition of the Waste Management system in Makassar City. It covers regulations, the amount and composition of waste, as well as the waste management system from collection, transportation, to final disposal. The third stage was to investigate the potential of landfill waste through landfill mining methods. The fourth stage assessed scenarios for biological waste management in Makassar City. The next stage was to assess scenarios for waste to energy in Makassar City. Therefore, the environmental impact was estimated based on scenarios from various waste processing activities multiplied by several emission factors available from the literature. Detailed information about each research method is explained in the following chapters. The research framework can be seen in Figure 1.1.

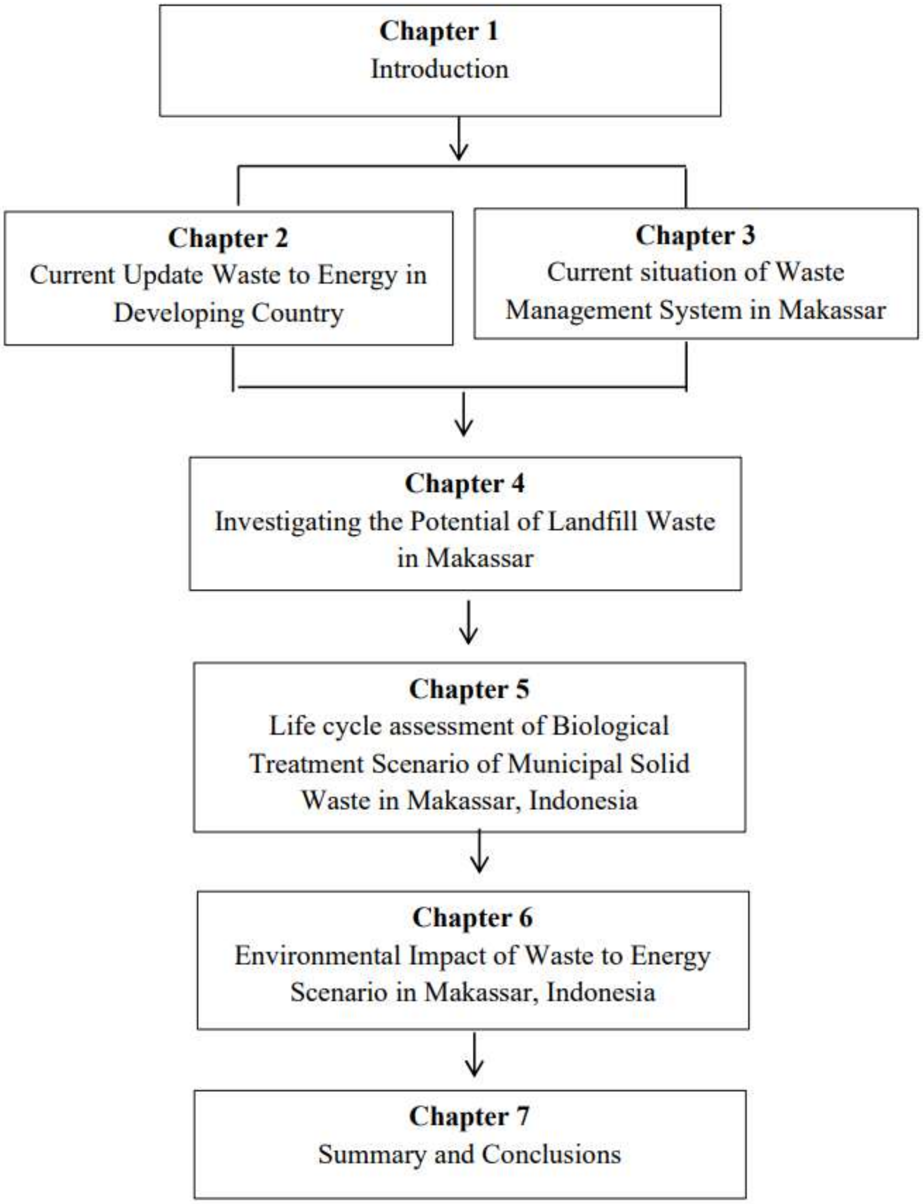

Figure 1. Research Framework

Chapter 2 Current Update Waste to Energy in Developing Countries

2.1. Introduction

Effective Municipal Solid Waste Management (MSWM) is a goal to be achieved in developing countries. Rapid population growth and lifestyle changes are the highest factors in urban garbage. On the other hand, landfills are beginning to be threatened by problems of overcapacity, land constraints, and poor environmental impact. The landfill has remained the primary choice for waste management in some countries for decades (Jeswani et al., 2013; Monni, 2012). This problem has reached worrying conditions, so it requires a sustainable solution to waste management. One of the highlighting approaches is waste-to-energy technology (WTE), which has now been widely applied in developed countries due to the development of renewable energy sources with efficient land use (Nanda & Berruti, 2021). Some previous studies related to Waste to Energy from Asian countries, such as China, aimed in 5 years that electricity generated from waste combustion technology would increase by 10%, reaching a 30% share of the total energy mix (Zhou et al., 2014). In Japan, most of the Municipal Solid Waste (MSW) that is 80% is handle by incineration. In this process, energy recovery has been included in a certain proportion of waste incineration plants (Tabata, 2013). In South Korea, the amount of energy produced from mixed waste (combustion) contributes more than 23% of renewable energy production (Ryu, 2010).

Most recent research suggests that combustion, anaerobic digestion, and pyrolysis are the most dominant Waste to Energy (WtE) processing. However, the researchers focused on developing more efficient energy processes, the most popular in the economic and environmental fields (Boloy et al., 2021). It is also mentioned that WTE plants have significant environmental benefits and excellent external benefits (Lim et al., 2014; Tsai & Kuo, 2010) ,as well as significant impacts on society and the environment (Pavlas et al., 2010).

Bibliometric is useful for mapping literature and quantitatively analyzing developments and growth in scientific publications (Du et al., 2014). Bibliometric techniques have been applied in various research in energy-related fields such as alternative energy research (Mao et al., 2015), solar energy (Du et al., 2014), energy efficiency (Du et al., 2013), Waste to Nergy technology (Boloy et al., 2021). Previous researchers have examined many methods of sustainable energy generation, considering factors such as cost (Fazeli et al., 2016), environmental impact using the Life Cycle Assessment (LCA) technique (Muis et al., 2023; Vandermeersch et al., 2014), and the Analytical Hierarchical Process (AHP) (Arafat et al., 2015; Toniolo et al., 2014).

The bibliometric study comprehensively analyzes waste-to-energy-related literature for effective municipal solid waste management in developing countries (Ndou & Rampedi, 2022). Also, to obtain various publication characteristics, such as publication types, subject categories, institutions, countries, year trends, and content analysis of keywords and titles.

The study will include a variety of relevant research articles, conference papers, and other scientific publications. The focus will be on exploring current knowledge about waste-to-energy technologies, their implementation in developing countries, and related environmental and socio-economic impacts.

The study aims to identify and evaluate research trends in the Scopus database using VOS viewer software in Developing countries that research WTE and influential publications in this field.

2.2. Research Methodology

2.2.1.Data Source

Data sources in this study are taken using Scopus Database. From previous research, Scopus was selected to obtain information from digital libraries and offer various queries through institutional subscriptions (Klapka & Slaby, 2018). The keywords used in this study are Waste Management, Municipal Solid Waste,

Waste to Energy. The data used is the literature published over the last 10 years, from 2014 to 2023. The study stage can be seen in the flow chart image (Figure 2).

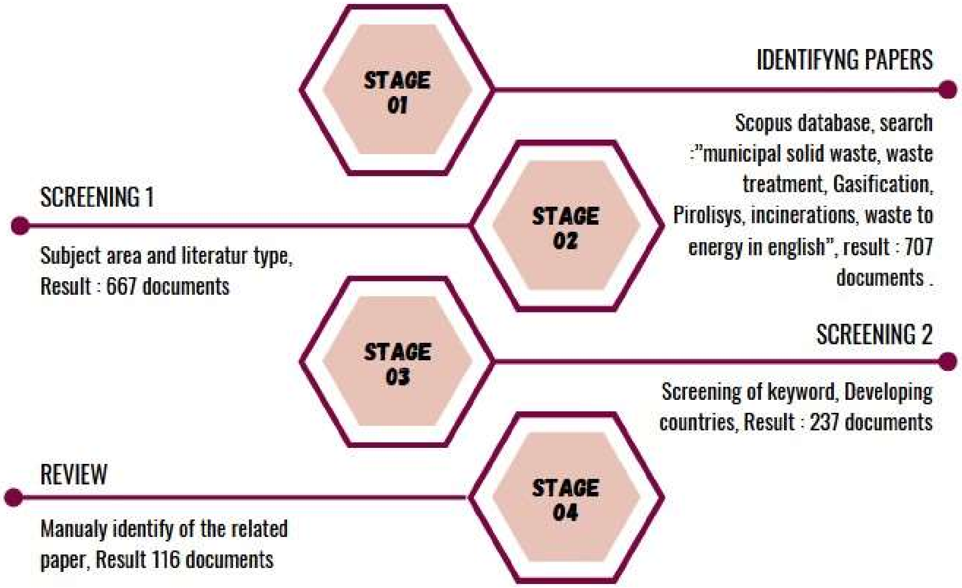

Figure 2. Flow Diagram for Article Selection Process

Stage 1 is identifying papers, the number of articles analyzed was 1880 in the form of journals, conference papers, and scientific reviews. The data distribution during the initial identification stage obtained a total of 707 literature documents. Stage 2 filtering on the title, abstract, subject area and type of literature results obtained 667 documents. The abstract filtering is done by selecting several components of methods, analysis, and results related to the reviewed article. The subject areas screening for filtering are energy, engineering, and environmental science topics. Stage 3 filtering (Keyword filtering developing countries), resulting in 237 documents. The final stage (stage 4) includes manually selecting documents that have relevance to Waste to Energy. The results were obtained from 116 documents to be analyzed using the Vos viewer software version 1.6.19.

2.2.2. Data analysis

Documents selected in the Scopus database of 116 articles are then downloaded in the *ris format and inserted into the VOS viewer software. In bibliographic metadata, the term "keyword" contains important information in scientific work and is usually used for indexing purposes (Ramadan et al., 2022). Furthermore, VOS viewer is used to illustrate trends in the form of bibliometric (Effah et al., 2023), i.e. publication maps with keywords or terms (term co-occurrence maps) will form a network (co-citation) that is connected based on related research. The more links between keywords or terms, the stronger the relationship between the terms. In this study, the calculation method uses a binary approach to analyze text data and a fractional approach to analyze bibliographic data. Then, network visualization and overlay in the analysis qualitatively.

2.3. Result and Discussion

2.3.1. Bibliometric Analysis Result

In this section, the results are discussed based on the co-occurrence of keywords, with author keywords selected because they tend to be more specific, precisely describing what is being researched. From the analysis results, 56 keywords were identified, with a minimum occurrence threshold set at five occurrences per keyword. Approximately 56 keyword nodes met this threshold, as seen in Figure 3. The identified keywords were divided into five clusters and formed 1427 links. As shown in Table 1, the keywords in the five clusters that appeared most frequently were named accordingly. For example, in cluster 1, the keyword MSW management is closely related to waste to energy, which suggests that most of the research analyses municipal solid waste currently processed into energy. A different color represents each cluster in the bibliometric mapping. The correlation between the number of nodes in the bibliometric map is related to the keywords appearing in the research. The larger the nodes, the more keywords appear in the research. The number of co-occurrences of more than two keywords indicates the number of publications in which the keyword appears together in the title, abstract, or list of keywords (Van Eck & Waltman, 2010).

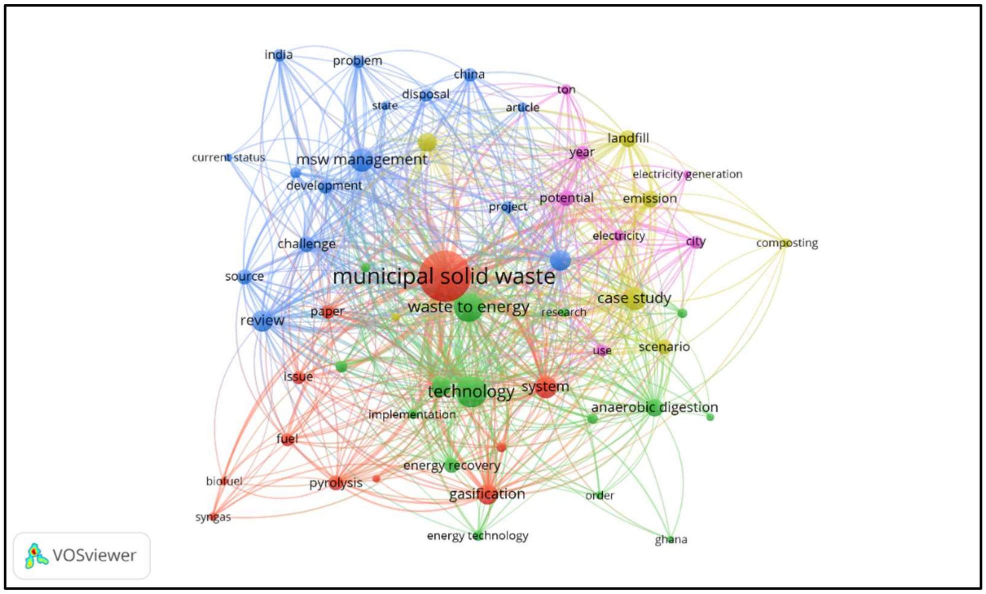

Figure 3. Co-occurrence of Author Keywords

Table 1. Number of co-occurrences and link of the keywords per clusters

Cluster	Keyword	Occurrences	Link
1 (15 items)	Article	16	49
	Challenge	41	53
	China	32	44
	Current Status	11	46
	Development	35	53
	Disposal	29	51
	Incineration	71	54
	India	26	47
	Msw Management	**88**	**53**
	Problem	29	51
	Project	22	46
	Review	76	53
	Source	36	54
	State	14	45
	World	21	52
2 (15 items)	Anaerobic Digestion	50	54
	Conversion	19	51
	Energy Recovery	37	54
	Energy Technology	19	53

Cluster	Keyword	Occurrences	Link
	Ghana	9	28
	Implementation	17	49
	Life Cycle Assessment	17	43
	Opportunity	14	50
	Order	12	47
	Perspective	23	52
	Research	15	50
	Sensitivity Analysis	10	46
	Technology	**156**	**54**
	Treatment	57	53
	Waste to Energy	138	54
3 (11 items)	Addition	10	46
	Biofuel	10	39
	Environmental Impact	16	48
	Fuel	28	50
	Gasification	69	54
	Issue	29	53
	Municipal Solid Waste	**429**	**54**
	Paper	32	54
	Pyrolysis	38	52
	Syngas	12	40
	System	81	54
4 (8 items)	City	29	50
	Electricity	21	52
	Electricity Generation	11	41
	Potential	**41**	**52**
	Ton	19	52
	Use	22	53
	Waste Conversion	32	53
5 (7 items)	**Case Study**	**88**	**54**
	Composting	14	43
	Emission	46	52
	Energy Production	12	47
	Generation	57	52
	Landfill	47	53
	Scenario	37	51

2.3.2. Density Visualization

As seen in Figure 4, the visualization of research distribution with the highest occurrence values is the keyword "Municipal Solid Waste" (429 occurrences) in cluster 3. This indicates that Municipal Solid Waste is relevant in waste-to-energy research. Municipal Solid Waste plays a crucial role in shaping a safe environment and is a potential renewable energy source. In recent years, Waste to Energy has become a trend implemented in developing countries in the Asia-Pacific region, especially in thermal processing (Alao et al., 2022). Occurrences of other keywords are related to technology in cluster 2, indicating an emerging trend in technology used in waste-to-energy research. In this study, several technologies were found mentioned in keywords such as Incineration (71 occurrences), Anaerobic Digestion (AD) (50 occurrences), Gasification (69 occurrences), Pyrolysis (38 occurrences), and Composting (14 occurrences). Thermal processes in Waste to Energy have been a focal point in research in developing countries in recent years.

In the co-occurrence analysis, in cluster 5, several keywords were found, namely case studies and emission factors in Waste to Energy, which are interrelated, along with environmental impact factors in cluster 3. These findings describe that Waste-to-Energy activities' emission factors and environmental impact are interesting research issues in developing countries and need further discussion. In cluster 2, the keyword "lifecycle assessment" was found to measure environmental impact. The lifecycle assessment method is an approach used to assess, identify, and analyze the potential environmental impact of various comparative scenarios (Ferronato et al., 2020).

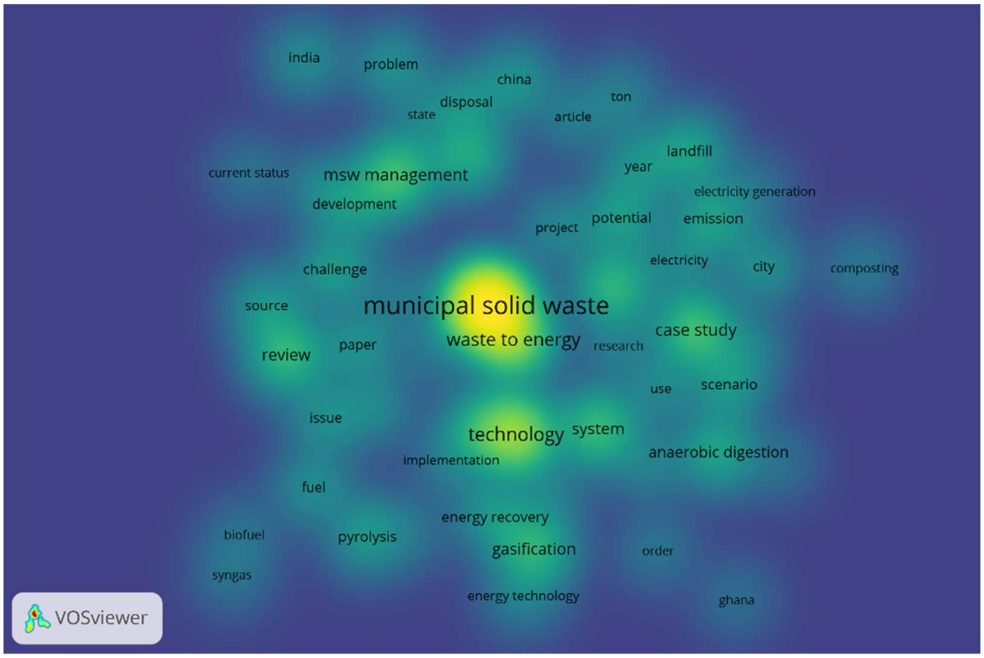

Figure 4. Density Visualization of Waste-to-Energy in Developing Countries.

2.3.3. Cluster analysis on bibliometric mapping.

The main topic in cluster 1 focuses on MSW (Municipal Solid Waste) management, which is interconnected with the review, country, incineration, problem, challenge, China, and India.

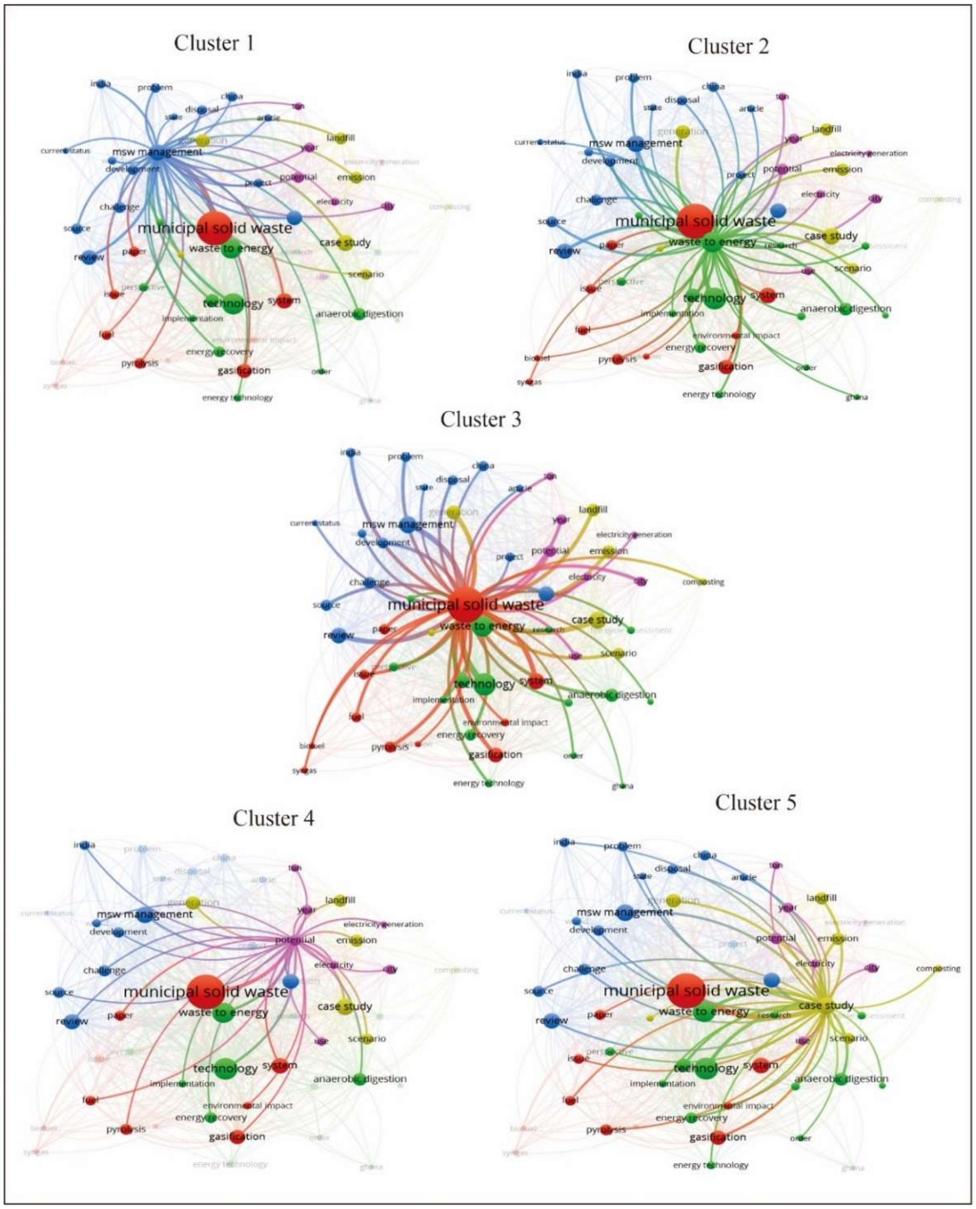

Figure 5. Keyword Cluster Map

According to Figure 5, these findings reveal that MSW management poses several problems and challenges in developing countries, and it currently attracts much attention in research, especially in countries like China and India. In cluster 2, the most frequently appearing keyword is related to waste to energy, strongly linked to technology, waste to energy, anaerobic digestion, energy recovery, and others

(Figure 5). These findings reveal that "Technology" in waste to energy is a significant aspect currently being applied in developing countries. In cluster 2, a strong association with life cycle assessment, the most used method for environmental impact analysis in waste-to-energy processes, is also found. In cluster 3, the mapping shows that keywords are centered around Municipal Solid Waste, related to processes used in waste treatment such as gasification, pyrolysis, biofuel, and others. In cluster 4, the focus is on the potential of Waste to Energy, linked to electricity, waste conversion, city, and other items. In cluster 5, the most frequently appearing keyword is "case study," which is interconnected with landfill, emission, and other items. In the case of Waste to Energy research, case studies are efforts to reduce emissions from the amount of waste ending up in landfills.

2.3.4. Trend of Waste to Energy Research

The Waste to Energy (WtE) sector is experiencing significant growth and transformation in developing countries. The need to address waste management challenges, coupled with the demand for renewable energy, has driven extensive research and investment in WtE technologies. The increasing trend of Waste-to-Energy (WtE) research worldwide and in developing countries can be observed in Figure 6. Publications related to Waste to Energy first entered the Scopus database in 1978, while in developing countries, research about waste-to-energy was identified in 2004. The growth of WtE research has continued to experience significant increases up to the present, which holds for developing countries as well.

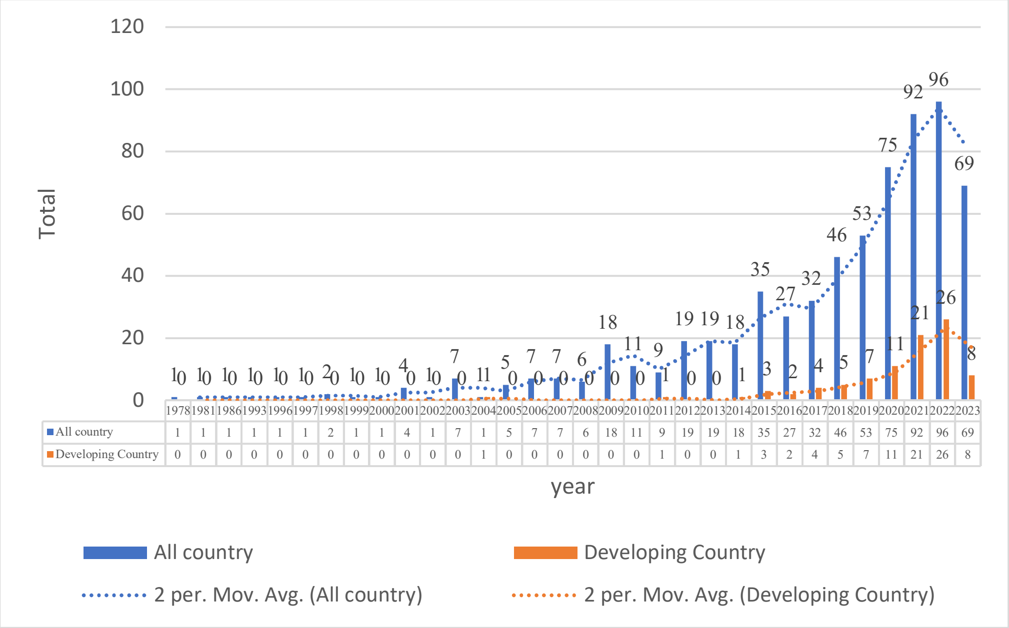

Figure 6. Number of WtE research in All country and Developing country

The research trends of the last five years can be observed in the bibliometric mapping visualization. As shown in Figure 7, the color gradient from blue, green, and yellow indicates research trends. The blue color in the figure represents research conducted before 2019, the green color indicates rapidly evolving research trends, and the yellow color signifies recent research trends after 2021. The figure illustrates the research potential related to Municipal Solid Waste connected to converting Waste to Energy. Following that, research on technology in Waste to Energy becomes prominent, with some studies focusing on conversion processes such as gasification and anaerobic digestion. The technology in waste-to-energy represents a trending research pattern widely applied in developing countries. Meanwhile, the yellow color associated with keywords like biofuel and electricity indicates recent research in the field of Waste to Energy.

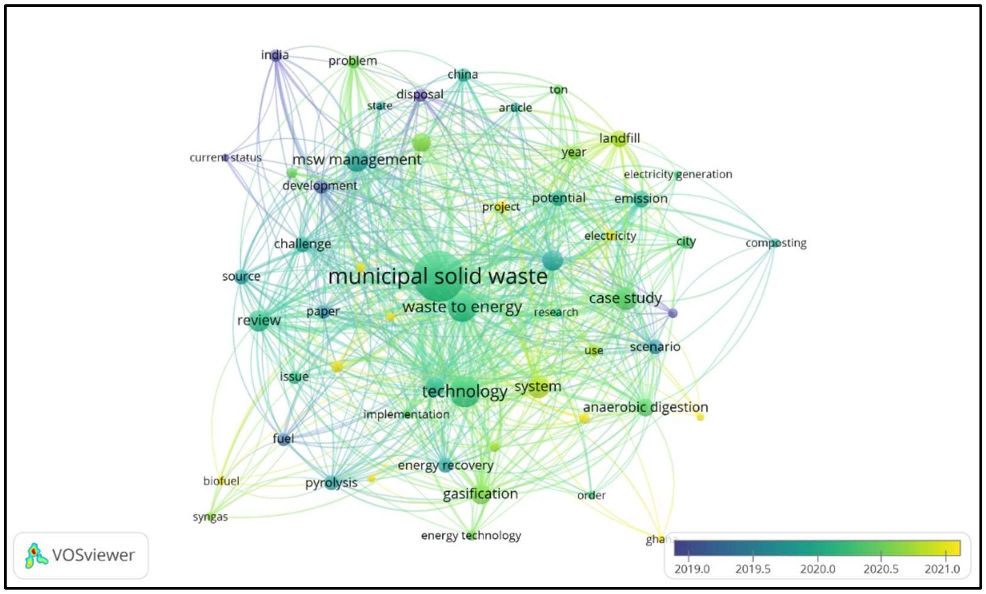

Figure 7. Visualization of Research Trend

2.4. Summary

The results of the bibliometric analysis reveal insightful patterns in waste-to-energy research. This research conducts a review and bibliometric mapping of scientific literature related to waste-to-energy (WTE) in developing countries. The article screening process in the Scopus database identified 116 articles related to Waste to Energy in developing countries. Based on the analysis results, keyword mapping was obtained and divided into 5 clusters. The analysis revealed keywords with the highest occurrence value, mainly related to "Municipal Solid Waste" in cluster 1. Another keyword with the most increased occurrence was related to "technology," indicating a technological trend in waste-to-energy widely used in developing countries, such as incineration, anaerobic digestion, pyrolysis, and composting. In another cluster, the keyword "life cycle assessment" was the most used method for assessing environmental impacts in waste-to-energy research. On the other hand, based on research trends, it was found that global research on Waste to Energy began in 1978. However, waste-to-energy research started in developing countries in 2004 and has significantly increased since then.

In the visualization of research trend mapping, keywords such as biofuel and electricity point to current research trends in the field of Waste to Energy.

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Chapter 3 Current Situation of Waste Management in Makassar, Indonesia.

3.1 Introduction

Makassar City is one of the cities in South Sulawesi and serves as the administrative center of the South Sulawesi province. The city of Makassar comprises hills, lowlands, and the sea, along with several small islands inhabited by some of the city's residents.

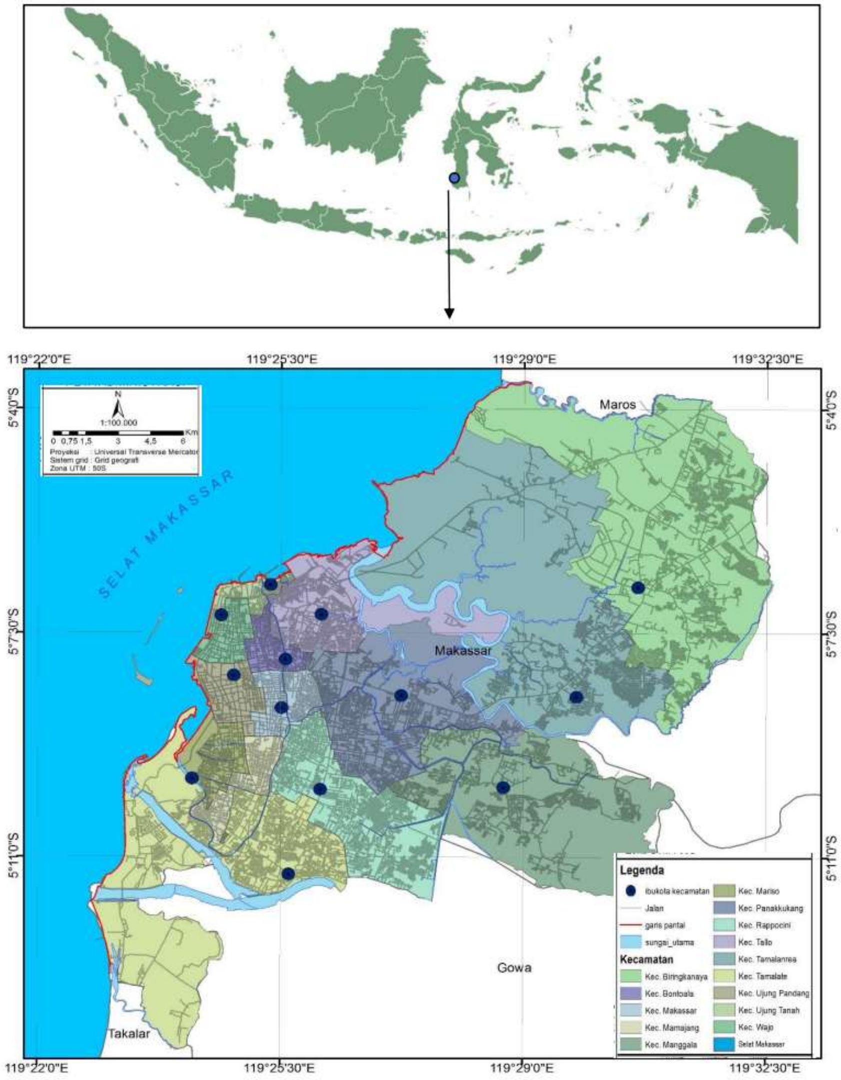


Figure 8. Makassar City Map

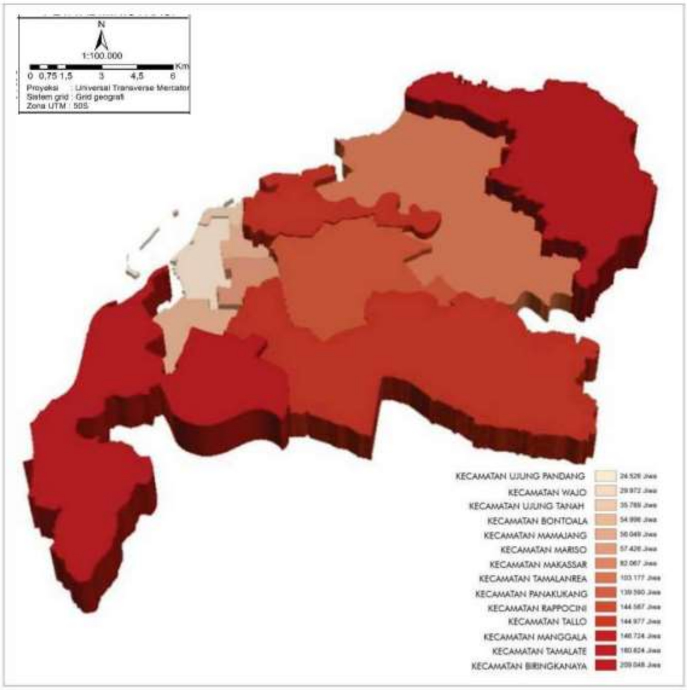
Geographically, Makassar City is located between 5°8'6.19" S and 119°24'17.38" E, covering an area of 175.77 km². Administratively, Makassar City comprises 14 districts and 143 sub-districts (figure 8). Makassar City is bordered by:

- North: Maros Regency
- East: Maros Regency
- South: Gowa Regency
- West: Makassar Strait

According to records from the Paotere Maritime Meteorological Station, the average air humidity is around 77 per cent, the air temperature ranges from 26°C to 29°C, and the wind speed is 4.2 knots. The average elevation of Makassar City ranges from 2 meters to 22 meters above sea level.

3.2 Demographic Aspects

Makassar City has evolved from merely being a gateway to being positioned as the living room of Eastern Indonesia. As a metropolitan city, Makassar grows with various potentials, one of which is its population.



(Source: Makassar city government, 2022)

Figure 9. Population in Makassar City

The increasing population of Makassar, which has now reached 1,424,470 people (BPS, 2022), positions it as a metropolitan city. Figure 9 shows the population distribution in each district of Makassar City. The highest population is in districts designated for integrated residential areas and the city center. The growth in population is typically accompanied by an increase in waste generation, a phenomenon commonly observed in developing countries, including Indonesia.

3.3 Waste Management Regulation

According to Law No. 18 Year 2008 on Waste Management, the types of waste covered are: (1) household waste, (2) waste like household waste, and (3) specific waste. The waste management mechanism outlined in the law includes waste reduction activities aimed at minimizing waste generation from producers such as households and markets, reusing waste at its source and at processing sites, and recycling waste both at its source and at the processing plant. Specific regulations on waste reduction will be detailed in a separate Ministerial Regulation.

Municipal waste management options are typically organized through a "waste hierarchy" (Figure 10), first introduced by the European Union in the EU Framework Directive on Waste in 1975 (Jamas & Nepal, 2010). This framework has subsequently been embraced by countries worldwide, including Indonesia. The hierarchy prioritizes prevention at the highest level and places disposal at the lowest level. It functions as a set of flexible guidelines rather than strict mandates for formulating waste policies.

The Makassar City Regional Government's policy for managing solid waste is outlined in Regional Regulation Number 4 of 2011 concerning Solid Waste Management. This regulation serves as a crucial foundation for implementing regional autonomy, aiming to improve the quality of public services provided by local governments to the community. It reflects the local government's dedication to addressing the solid waste issues in Makassar City and delivering optimal waste management services to the community.

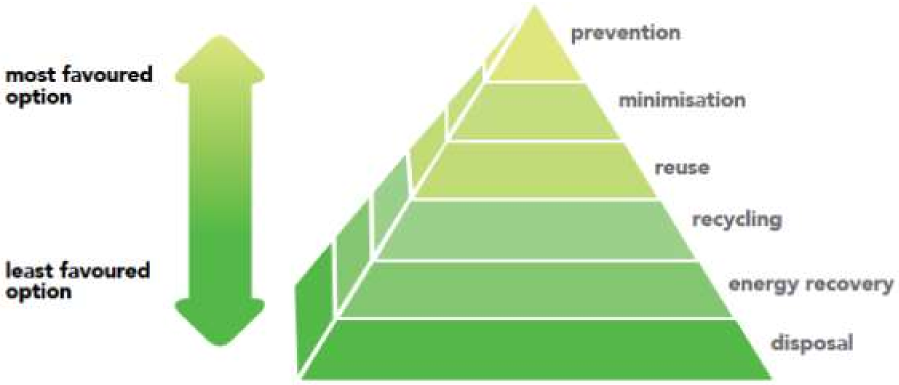


Figure 10. Hierarchy of waste management

Source: Ministry of Energy and Mineral Resources, 2015

According to Regional Regulation Number 4 of 2011, the local government of Makassar City has enacted several policies. Empirically, as previously indicated, the Makassar City Government has supplied 248 garbage trucks. The Tangkasaki truck fleet includes 210 units, with 15 units allocated to each sub-district across the 14 sub-districts of Makassar City. Additionally, there are 145 Arm-Roll trucks on operational standby, 21 units of special private garbage fleets (serving hotels, restaurants, industries, and housing areas), and 603 garbage bin motorcycles available in Makassar City. The city also employs 620 cleaning staff, with 420 distributed as 30 people per district across 14 districts, and 143 managers. There are approximately 57 available fleet drivers who are official honorary employees, 12 official fleet drivers, and 42 individuals responsible for transporting waste from containers.

Based on the government policy in Presidential Regulation Number 35 of 2018 concerning the acceleration of development of waste processing installations into Environmentally Friendly Technology-Based Electricity. Waste-Based Power Plants, referred to as Waste to Energy, are waste processors that convert waste into environmentally friendly technology-based electricity that meets quality standards according to laws and regulations and can significantly reduce waste volume and have been tested. The developer of Waste to Energy is the Waste Manager and electricity provider who signs a cooperation contract regarding the supply of waste as raw material for conversion to electricity with the Regional

Government and a contract for the sale of electricity with PT PLN (Persero) as the buyer of the electricity from WtE. This regulation is a government program for several major cities in Indonesia, including Makassar.

3.4 Waste Management System

The waste management system in Makassar City involves direct waste collection (door-to-door) and transportation to the final waste processing site (TPA). Like in other cities in Indonesia, waste management in Makassar City is a challenging urban issue. This is influenced by several factors, such as:

a. High urbanization rates, leading to increasing waste production,
b. Community behavior in waste handling
c. Implementation of less stringent regulations in waste management
d. Relatively high financing requirements, as well as several other technical constraints

Table 2 describes the waste in the landfill that comes from various sources. Most of the waste originates from households, constituting approximately 28.87% of the total, including settlements with high, middle, and low incomes (Makassar City Government, 2021). The highest volume of waste comes from low-income settlements, amounting to 21.33 m3/day. The lowest waste source is from worship facilities at 1.49%.

Table 2. Source of Waste

Source of Waste	Percentage
Household Waste (High Income)	2.24
Household Waste (Middle Income)	5.3
Household Waste (Low Income)	21.33
Market	15.79
Business Area	3.69
Office Area	3.82
Education Area	2.02
Terminal	1.66
Port	3.67
Hotel	3.69
Hospital	3.62
Worship Facilities	1.49
Industrial Area	2.18

Source of Waste	**Percentage**
Open water bodies	14.76
Tourist Beach	14.76
Parks	2.74
Others	8.89

Based on the data obtained from table 3, the average waste production per person in Makassar is 0.62-0,83 kg per day. Given that the average household in Makassar consists of four people, an average household in Makassar produces 2.48-3,32 kg of waste per day.

Waste production in 2021 reached 900-1200 tons per day, with the composition components of the waste being food scraps, paper, wood, textile fabrics, leather scraps, plastic, ferrous-non-ferrous metals, glass, and others (such as soil, sand, stone, ceramics). Organic waste dominates the waste composition in Makassar City at 55%-65%, with the remainder being inorganic waste.

Table 3. Population Projection and Waste Generation in 2025

No	**District**	**r (%)**	**Population Projection in 2025**	**Waste Generation Rate (kg/person/Day)**	**Projected Waste Generation in 2025 (kg/day/person)**
1	Mariso	0,64%	58909	0,56	33154,03
2	Mamajang	0,08%	56229	0,82	45961,67
3	Tamalate	0,84%	186958	0,56	105220,14
4	Rappocini	0,10%	145171	0,66	95319,57
5	Makassar	0,24%	82860	0,68	56626,82
6	Ujung Pandang	0,06%	24586	2,39	58642,59
7	Wajo	0,46%	30526	1,33	40495,66
8	Bontoala	0,44%	55971	1,02	57001,08
9	Ujung Tanah	0,94%	37151	1,15	42812,26
10	Sangkarang	0,93%	14661	0,40	5893,61
11	Tallo	0,64%	148719	0,34	49820,82
12	Panakukang	0,12%	140267	0,64	90219,49
13	Manggala	1,17%	153737	0,54	82403,18
14	Biringkanaya	1,03%	217836	0,59	128435,95
15	Tamalanrea	0,14%	103758	0,76	79250,06
Total		0,58%	1457270	0,83	1208096,26

Waste Transportation System

The waste collection pattern in Makassar City is organized based on district areas to facilitate the waste collection. The waste collection system can be implemented through different methods, depending on the collection system used. Suppose the waste collection and transportation employ a transfer station (transfer depot) or indirect system. In that case, the transportation process can utilize the Hauled Container System (HCS) or the Stationary Container System (SCS). The stationary container system can be carried out mechanically or manually.

The mechanical system uses compactor trucks and containers that are compatible with the truck type. In contrast, the manual system uses labour and containers as garbage bins or other receptacles. In recent years, the waste collection pattern in Makassar City has utilized a door-to-door system (figure 11). This direct collection system involves simultaneous waste collection and transportation. The process is managed by district fleets consisting of Fukuda vehicles and several dump trucks, which are directly overseen by each district in Makassar City. These vehicles are assigned specific responsibilities for the neighborhoods they serve. The following outlines the operational process of the door-to-door system:

1. Vehicles depart from the pool and head directly to the waste collection route.
2. The garbage truck stops at the roadside of each house being serviced, where workers collect the waste and load it into the truck bed until complete.
3. Once filled, the truck proceeds directly to the Transfer Station, processing site, or landfill (TPA).
4. After unloading at the processing location, the vehicle returns to the following service route until the last shift then returns to the pool.

This structured approach ensures efficient waste management and service delivery across the city.

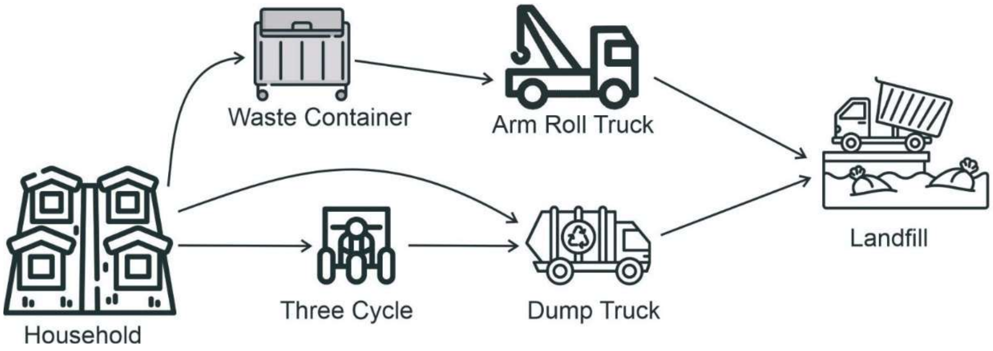


Figure 11. Door-to-Door Waste Collection System

The amount of waste transported to the landfill is approximately 900-1200 tons per day. A total of 319 trucks are used for waste transportation, with each truck consuming 15 liters of fuel per day. The capacity of the garbage trucks used is 2.5 tons per truck.

Landfill

The Tamangapa landfill is the destination for all waste in Makassar city, operating since 1994 with an area of 16.8 hectares (Ministry of Environmental 2018). As seen in figure 12 The Tamangapa landfill is divided into four passive zones, one active zone, and one preparation zone that will become a passive zone. The landfill fully uses the open dumping method, which scores the lowest on indicators 23 and 24. The waste brought to the landfill is only disposed of without further processing. Additionally, some types of waste that should not be in the landfill, such as electronic waste and construction waste.

The landfill's operations also do not implement daily cover at the site, allowing water to seep into the ground. The landfill site is also located near residential areas. The existing leachate ponds have not been able to provide maximum results, mainly due to the lack of capacity compared to leachate production (Sharma & Ganguly 2018). This problem will worsen during rainfall. Improper leachate handling can cause pollution and soil contamination (Periathamy 2011; Rao 2017).

The government needs to immediately think of a solution to the dire conditions at the Tamangapa landfill. The landfill has exceeded its capacity to accommodate waste production and is estimated to only be able to operate until 2023. The height of the waste has reached 40-50 meters.

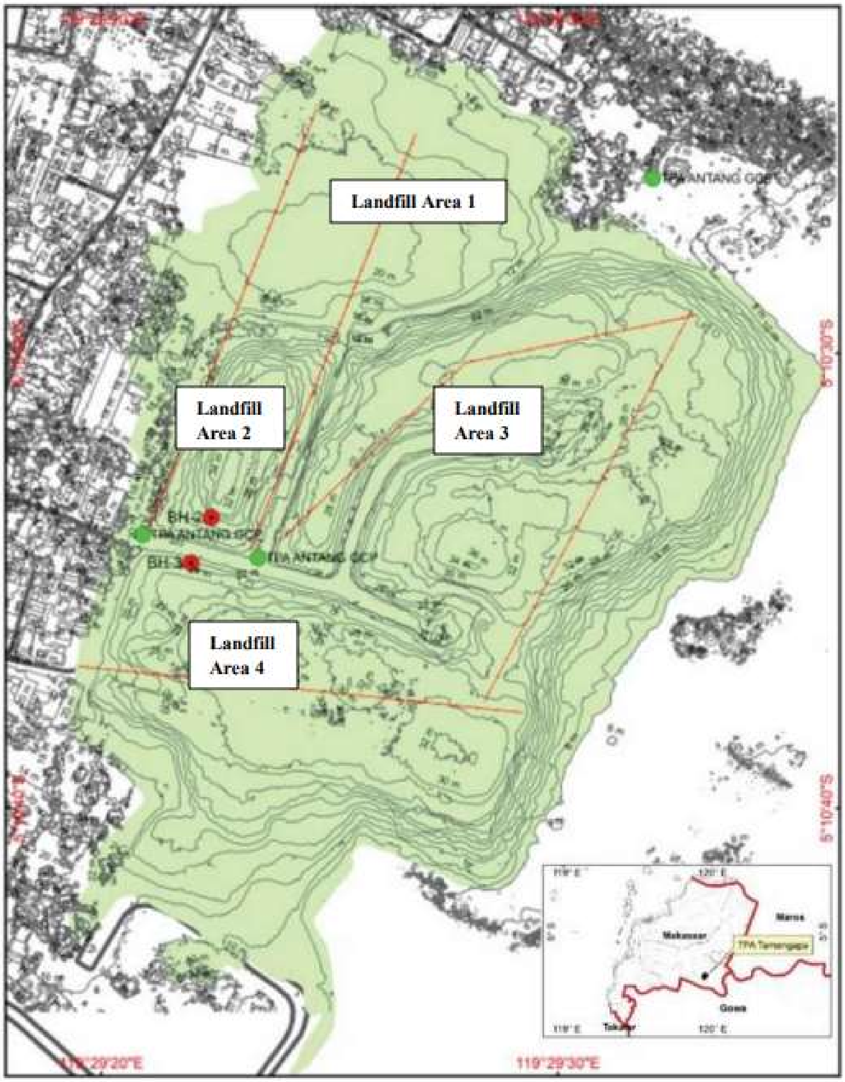


Figure 12. Tamangapa Landfill

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Kementerian LHK Republik Indonesia (2018d SIPSN - Fasilitas Pengelolaan Sampah Kota Makassar Periode 2017 – 2018

Waste management mechanism in Law No. 18 of 2008

Chapter 4 Investigating the Potential of Energy Recovery from Landfill Waste in Makassar

4.1 Introduction

The demand for various materials has significantly increased over the past few decades. Rapid industrial advancements and the continuous population growth in large cities will increase both organic and inorganic waste (Mourshed et al., 2017). The rising demand for a wide range of materials covers various sectors in modern society, including household products, agriculture, electricity and electronics, medical and health, and packaging industries (Zhou et al., 2014; Kibria et al., 2023; Jian et al., 2022). In the context of Municipal Solid Waste (MSW), inorganic waste such as plastics, metals, and glass make up a significant portion, with plastics alone contributing to about 10-13% in the form of bottles, packaging materials, containers, etc. (Duru et al., 2019). Disposable materials, such as food packaging and packaging bags, are predicted to contribute approximately 50% to plastic waste and are often discarded without processing (Duru et al., 2019). Due to the difficulty in decomposition, a significant portion of inorganic waste is in landfills (Geyer et al., 2017; Van Roijen & Miller, 2022). This poses a severe environmental threat currently faced in large cities worldwide. The volume of inorganic waste from MSW has increased dramatically over the years. Ineffective Municipal Solid Waste Management can cause pollution problems in water, air, and soil (Khair et al., 2019; Muis et al., 2021) and can also have an impact on human health (Fariz et al., 2023; Yunus et al., 2019).

As a representative developing country in the world, Indonesia has experienced rapid population growth. In 2021, Indonesia's estimated total national waste reached 68.5 million tons, with 17 percent of it contributed by plastic waste (Ministry of Environment and Forestry, 2021). As one of the major cities and a metropolitan city with a strategic location in the Eastern Indonesia Region, Makassar City had a total population of 1,432,189 people in 2022 (Makassar Bureau of Statistics, 2023). The rapid development and lifestyle changes have led to an increase in waste volume in Makassar City ; it's currently averaging 1139 tons a day (Muis et al., 2023). The characteristics of waste in Makassar City are dominated by organic waste, accounting for 55% of the total, while non-organic waste, including plastics, rubber, cane, and metal, constitutes 45%. The suboptimal waste management system results in a significant portion of the waste ending up in landfills, with approximately 16% being plastic waste. The amount of plastic waste reached 294 tons per day in 2020, experiencing an increase from the previous year, which was approximately 258 tons per day. (Ahmad Husain, 2021).

Meanwhile, Makassar, the largest landfill in the eastern region of Indonesia known as Tamangapa Landfill, still employs the open dumping method in its operations (Madani, 2023), and waste is mixed and buried without proper treatment. Currently, the landfill has exceeded its capacity. It has become a common understanding that relying on landfills as the primary waste management solution will have long-term environmental implications. Landfill mining has emerged as one scenario to address this issue. Landfill mining is centered around optimizing the resource capacity of landfill sites. Landfill mining is the act of excavating, treating, or recycling waste that has been held in dumps, utilizing waste materials with a high calorific value for recycling purposes. (Krook et al., 2012). Research related to landfill mining has been conducted in various countries (Hermann et al., 2016; Jagodzińska et al., 2021; Pecorini & Iannelli, 2020; Wolfsberger et al., 2015).

According to regulations, the Ministry of Public Works in the Republic of Indonesia (MoPW) establishes the standards for landfill mining, and meeting at least one of these criteria is a prerequisite for conducting landfill mining. The criteria include (1) the landfill causing environmental impact, (2) the government being unable to identify alternative suitable locations for landfills, and (3) The landfill responsible for the management of non-hazardous waste. (Indonesia Ministry, 2013) (Kristanto et al., 2020). The Makassar landfill meets several criteria, with some indications such as groundwater pollution in the surrounding area (Ummu Salmah & Atjo Wahyu, 2023) and unsafe air pollution for human health (Abbas et al., 2019). Also, it has yet to find a new area for waste disposal.

Plastic, as a material derived from non-renewable resources, has become one of the main wastes in mining activities. Plastic waste that pollutes the environment in microplastics can contaminate water sources such as wells because they are recycled using harmful chemicals. In addition, the decomposition process can take a long time, hundreds of years (Haedar et al., 2019). On the other hand, plastic waste has the potential for recycling due to its high calorific value (Krook et al., 2012). Therefore, as an initial step to anticipate threats and harness the potential of plastic waste, research on the investigation of waste through landfill mining methods is needed. The study aims to investigate the potential of energy recovery in the landfill waste by drilling waste processes in landfills in several zones at still active landfill sites, which have been operating for 25 years, and inactive landfill zones. (which has been operational for more than 20 years).

4.2 Methodology

4.2.1 Study location

This research was conducted in Indonesia at the Makassar City Landfill, located in the eastern part of Makassar, precisely in the Tamangapa Village, Manggala Sub-district, Makassar City.

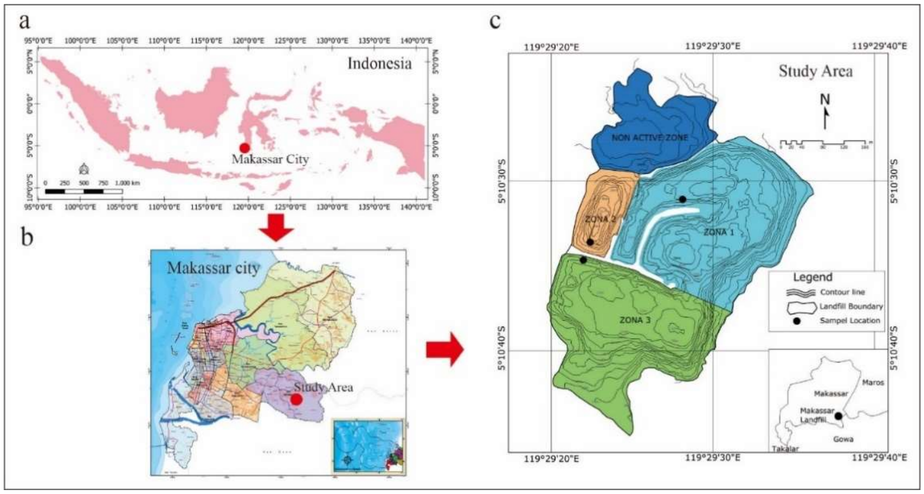

Figure 13. The Map of Study Area: (a) Indonesia, (b) Makassar city, (c) Landfill Tamangapa Area (The Sampling Locations)

As one of the metropolitan cities in Indonesia, Makassar encompasses an area of 175.77 square kilometres and includes 14 wards. Figure 13 shows the map of Indonesia, and the arrow points to the location of the research area (5°10'34.60"S, 119°29'26.90"E).

The Makassar City Landfill, namely Tamangapa Landfill, has been in operation since 1993, covering an area of 18,827 hectares (Table 4), making it the largest final disposal site in Eastern Indonesia. It is situated at an elevation of 4 to 10 meters above sea level, with a maximum surface pile height of 38 meters above sea level. The Makassar City landfill is divided into four zones. Old landfill zone and zone 1 are zones that are no longer in use. Meanwhile, zones 2 and 3 remain in use (Figure 14).

Table 4. Area and Total Waste in Makassar Landfill

Zone	Area (Hectares)	Waste Volume (m^3)
Old Landfill (Not Survey)	3,855	617.739,47
Zone 1	6,38	1.444.509,4
Zone 2	1,252	261.377,84
Zone 3	7,34	1.695.535,8
Total	18,827	4.019.162,51

Figure 14. Waste piles in one of the zones in the Makassar City landfill (a). The process of transferring waste from garbage trucks using excavator (b).

4.2.2 Data Collection

Quantitative data in this research employs surveys, measurements, and analysis to quantify waste's volume, density, and composition in landfills. The research method consists of several stages that can be outlined in the following flowchart.

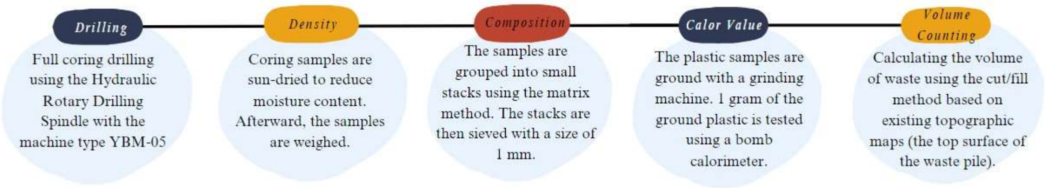

Figure 15. Flowchart

4.2.3 Drilling

The sampling method involved full coring using a Hydraulic Rotary Drilling Spindle with a machine type YBM-05. Samples were taken at three locations.

Table 5. Sampling locations and depth of drilling

Location	Sampling point	Depth of drilling (meter)
Zone 1 (Inactive Zone)	X: 5°10'31.12" Y: 119°29'28.19"	0-17
Zone 2 (Active Zone)	X: 5°10'33.06" Y: 119°29'22.41"	0-18
Zone 3 (Active Zone)	X: 5°10'34.6" Y: 119°29'21.4"	0-13

Zone 1 is inactive and no longer in use, containing decomposed waste of over 20 years. Zone 2 and Zone 3 are active zones still in operation, containing decomposed waste in the lower layers and fresh waste stacked on the upper layers up to the present. Samples were taken by excavating material at every meter depth in each zone. Table 5 shows that Zone 1 has an excavation depth of 0-17 meters, Zone 2 has a depth of 0-18 meters, and Zone 3 has a depth of 0-13 meters. This excavation is the maximum depth that can be accessed due to the nature of the waste and the type of equipment used for excavation. The core barrel used at locations 1 and 2 had a diameter of 3 inches and a core length of 100 cm, while location 3 used a core barrel with a diameter of 2.5 inches. The drilling process and the resulting core samples are shown in Figure 3. The next step involves preparing the samples for the determination of density, composition, and calorific value.

4.2.4 Density (kg/m^3)

The density of waste samples is measured by considering the diameter and length of the core barrel currently in use. Zones 1 and 2 indicate a waste sample volume of 4,558 x 10^{-3} m^3 per meter of drilling depth, while location 3 has a waste sample volume of 3,165 x 10^{-3} m^3 per meter of drilling depth. Before measuring the density, the waste samples were exposed to sunlight for several days at the Landfill Site drilling location. Consequently, the moisture content of the waste samples, particularly the outer core part (defined as wet samples), has decreased. After completing the weighing process, the next step involves redrying the wet samples in an oven for 30 minutes at 100ºC. This redrying process facilitates subsequent processes, such as the composition and grinding processes (through mesh 60), for laboratory testing. Before commencing the composition process, the redried samples are weighed again, defined as dry samples.

4.2.5 Waste Composition

The method used to determine waste composition in landfills uses the Indonesian National Standard (SNI) 19-3964-1994. This standard provides guidelines related to the methods of collecting and analyzing waste and the classification or composition of various types of waste.

Data was collected by excavating four waste mounds at the landfill to obtain samples of 500 liters per mound at depths of 3 and 6 meters. The excavated material was then stored in five drums for each depth. The excavation of the waste mounds was conducted using an excavator. After drying and re-weighing, the waste samples are arranged using the matrix method in small stacks. This is done to facilitate the sorting and separation process of compost or soil adhering to plastic or cloth, as illustrated in the figure. The next step involves sieving each small stack with a size of 1 mm to separate the compost from the stack. Subsequently, sorting is done based on categories such as plastic, cloth, wood, stone, glass, rubber, etc. The types of waste that have been sorted are then placed in plastic bags for weighing to determine their composition. This process is repeated for all depths at each sampling point.

4.2.6 Calorific Value

To determine the calorific value, a bomb calorimeter test is conducted on the samples. An oxygen bomb calorimeter is used to determine the caloric content of various samples (Trombley et al., 2023). The samples are first pulverized and then refined using a 60-mesh sieve. One gram of plastic powder is tested for its calorific value using a bomb calorimeter.

4.3 Result and Discussion

4.3.1 Source of Waste

Waste accumulated in the landfill comes from various sources. Most of the waste originates from households, constituting approximately 21.33% of the total, including high income settlements, middle-income, and low-income settlements (Makassar City Government, 2021). Waste from city facilities comes from markets, business districts, office areas, educational zones, terminals, railway stations, ports, hotels, hospitals, and facilities of worship (Figure 16). Market waste from trading activities is the most dominant source of waste in urban facilities, accounting for about 15.8%. Other waste sources include industrial areas, open waters, tourist beaches, and parks.

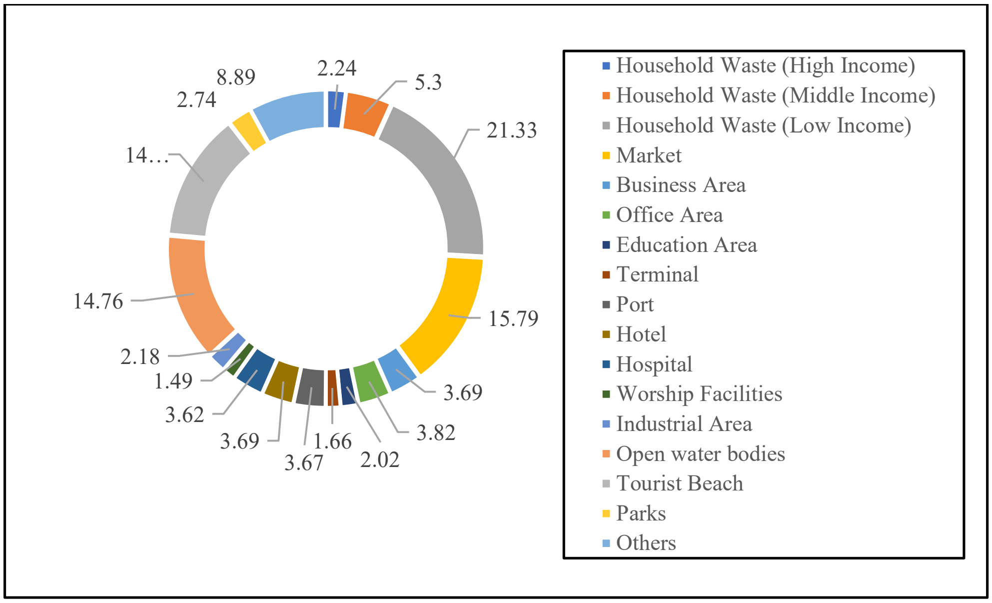

Figure 16. Source of Waste based on Location.

Characteristics of household waste generally contains single-use items. Plastic waste from household waste in Indonesia, including Makassar, consists of plastic bags, plastic packaging from food and product items, and plastic bottles. The composition of plastic waste ranges from 16% of the total waste. The following table 6 provides information about the application of various main plastic materials in household activities and their types.

Table 6. Application of Plastic Materials in Household Activities (Gwada et al., 2019)

Application of Plastic Materials	Type
Salad dressing containers, processed meat packages, water bottles, and plastic soft drink	PET
Milk bottles, shampoo bottles, oil jerry cans and toys	HDPE
Fruit plastic packaging, sweet trays, and blister packaging	PVC
Bread bags, frozen food bags, squeezable bottles, fiber, bottles, furniture, shrink wraps and garment bags	LDPE
Margarine and yoghurt containers, cap for containers, and wrapping to replace cellophane	PP

Application of Plastic Materials	Type
Egg cartons, fast food trays, and disposable plastic silverware	PS
This includes an item which is made with a resin other than the six listed above or a combination of different resins	Other

4.3.2 Waste Composition from Drilling

A lot of the waste in the landfill has already decomposed. In Figure 17, core samples at each location are predominantly composed of inorganic waste with various categories including plastic, fabric, rubber, glass, and others. As for organic waste, it consists of food remnants, vegetables, fruit peels, leaves, and grass, which are generally decomposed.

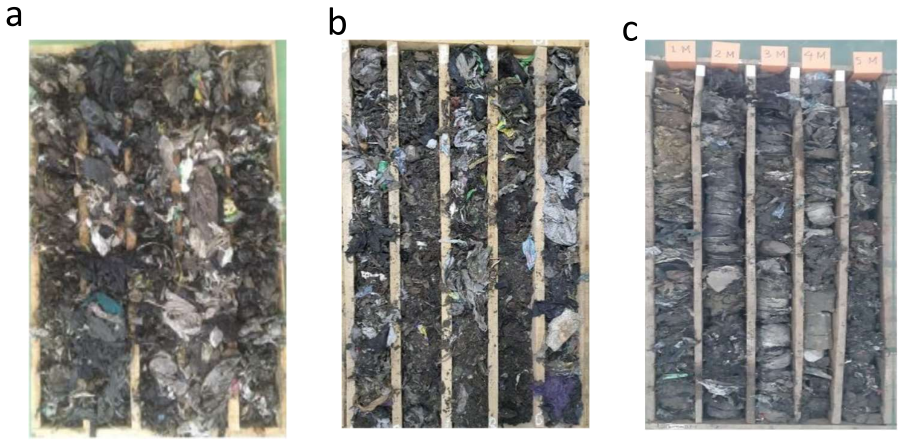

Figure 17. Drilling Sample (a) Zone 1 (b). Zone 2 (c) Zone 3.

Based on the drilling results, table 7 shows that in Zone 1, the organic and inorganic waste ratio averages 10-20% at a depth of the first 10 meters and 20-40% at the next 10 meters. The ratio of organic and inorganic waste in zone 2 is as follows: at a depth of 0-6 meters, approximately 10-20% is organic waste; at a depth of 6-9.5 meters, the organic composition increases to 20-40%, at a depth of 9.5-15 meters, around 10-20% is organic waste, and at a depth of 15-17 meters, the organic composition reaches 40-60%. At zone 3, the comparison between organic and inorganic waste is as follows: at a depth of 0-5 meters, the organic proportion reaches 20-40%. Furthermore, at a depth of 5-13 meters, the organic composition ranges from 5-10%.

Table 7. The Ratio Organic dan Inorganic Waste in Each Locations

Location	**Depth (meter)**	**Ratio of organic and inorganic waste (%)**
Zone 1	0-10	10% : 20%
	11-20	20% : 40%
Zone 2	0-6	10% : 20%
	6-9.5	20% : 40%
	9.5-15	10% : 20%
	15-17	40% : 60%
Zone 3	0-5	20% : 40%
	5-13	5% :10%

4.3.3 Density (kg/m^3)

The mass of a type of plastic waste in landfill mining is the measurement of the weight per unit of volume of the plastic waste buried in the landfill site. This type of mass is expressed in weight units (e.g., kilograms) per volume unity. (e.g., meter degree). In the context of landfill mining, the mass of plastic waste type becomes an important parameter as it affects various operational aspects and the sustainability of the waste extraction and management processes. The mass of plastic waste can vary depending on various factors, including the type of plastic, the conditions of degradation, and the level of waste density in the landfill.

The average wet density value at zone 1 is 0.451 ton/m^3, and the dry sample is 0.426 ton/m^3. At Zone 2, the average wet waste density is 0.528 tons/m^3, and the dry sample is 0.502 tons/m^3. Meanwhile, zone 3 is 0.989 ton/m^3 for wet samples and 0.728 ton/m^3 for dry samples. The density values per depth at each location are shown in Table 8.

Table 8. Density of The Samples in Each Location

Depth (m)	**Density (ton/m^3)**					
	Zone 1		**Zone 2**		**Zone 3**	
	Wet	Dry	Wet	Dry	Wet	Wet
0-1	0.410	0.373	0.188	0.183	0.790	0.771
1-2	0.291	0.265	0.231	0.209	0.946	0.844
2-3	0.308	0.273	0.362	0.350	0.941	0.926
3-4	0.259	0.231	0.369	0.324	1.119	1.101
4-5	0.228	0.208	0.278	0.264	0.632	0.611
5-6	0.258	0.228	0.290	0.255	1.093	1.056
6-7	0.316	0.304	0.618	0.576	0.958	0.950
7-8	0.296	0.289	0.874	0.861	1.060	1.033
8-9	0.284	0.274	1.018	0.970	1.083	1.060
9-10	0.222	0.186	0.697	0.645	1.371	1.361
10-11	0.761	0.752	0.491	0.463	1.013	0.961
11-12	0.670	0.651	0.690	0.673	1.119	1.096
12-13	0.757	0.731	0.334	0.311	0.732	0.728
13-14	0.856	0.817	0.403	0.392		
14-15	0.610	0.604	0.355	0.323		
15-16	0.693	0.647	0.667	0.634		
16-17	0.522	0.488	1.111	1.104		
17-18	0.379	0.356				
Average	0.451	0.426	0.528	0.502	0.989	0.961

4.3.4 Waste Composition in Landfill

The results of the waste drilling showed that the composition of plastic waste dominated the entire zone in both inactive and active zones. Figure 18 shows that in zone 1, the composition of waste is dominated by plastic waste, with an average value of 31%. Subsequently, the average composition of plastic waste in zone 2 is 22%, and in zone 3, it is 14%.

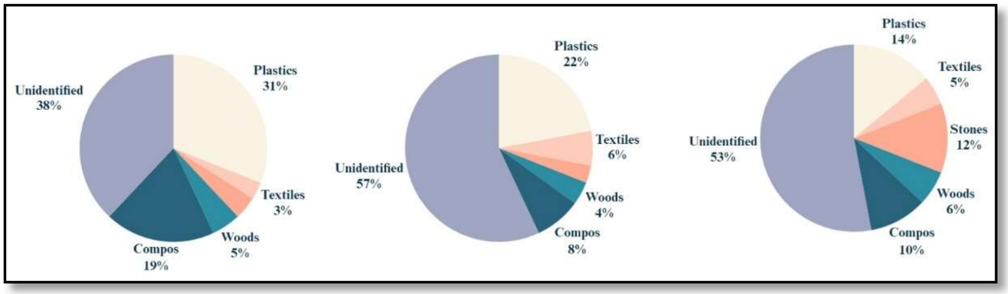

Figure 18. Composition of waste in (a). Zone 1 (b). Zone 2 (c). Zone 3

In the inactive zone on the surface of the waste pile at a depth of 1 meter, plastic waste composition is obtained at 51% (Table 9). In this zone, a significant amount of plastic waste is found, with compositions ranging from 16% to 63% up to a depth of 18 meters. In Zone 2, which is an active zone currently in use, the composition of waste at a depth of 1 meter ranges around 41%. Zone 3 is also an active zone currently in use. In this zone, the plastic waste composition is the lowest compared to other zones, ranging from 1% to 26%, observed up to a depth of 13 meters.

Table 9. Waste Composition in Each Landfill Area

Depth (m)	Waste composition (%)															
	Zone 1					Zone 2					Zone 3					
	Stone	Wood	Compost	Others	Plastic	Cain	Stone	Wood	Compost	Others	Plastic	Cain	Stone	Wood	Compost	Others
0-1	3	3	16	9	41	7	6	2	11	32	21	6	7	8	17	41
1 - 2	3	9	13	32	30	6	7	7	8	43	23	6	2	15	8	47
2 - 3	2	1	13	20	34	27	0	4	6	29	22	9	13	6	12	39
3 - 4	2	1	34	38	24	25	1	6	12	32	7	1	23	3	12	54
4 - 5	7	5	23	39	30	9	1	2	10	47	19	15	3	2	6	56
5 - 6	2	4	15	29	26	2	3	3	10	57	5	1	34	2	14	45
6 - 7	1	5	20	57	25	2	3	5	6	59	10	3	3	13	14	48
7 - 8	0	2	15	41	22	3	1	2	1	70	26	9	11	7	7	40
8 - 9	9	21	11	37	14	0	4	2	2	78	11	4	24	7	10	43
9 - 10	4	3	22	33	26	7	0	10	6	51	1	0	12	6	3	78
10 - 11	7	9	10	45	12	2	3	4	7	72	15	1	18	4	12	51
11 - 12	14	5	14	41	9	1	1	3	4	83	10	2	2	2	7	78
12 -13	4	8	11	44	29	6	2	1	10	52	10	3	5	7	13	61
13 - 14	4	3	28	44	12	3	9	3	11	62						
14 -15	2	2	36	39	21	4	3	2	8	62						
15 - 16	4	4	17	48	13	3	1	4	11	68						
16 - 17	3	6	25	47	5	0	1	2	11	80						
17 - 18	6	4	14	31												
Average	4	5	19	37	22	6	3	4	8	57	14					

Previous research at the Nonthaburi about the plastic component ranged from 24.6% to 44.8%, while the soil-like materials accounted for 27.9% to 56.6% of the overall weight. Polyethylene plastic carry bags accounted for the most significant percentage of plastic waste, ranging from 11.9% to 23.4% (Chiemchaisri et al., 2010). Moreover, plastics exhibit a high level of stability in comparison to other types of waste in municipal solid waste disposal facilities. In European countries, for instance, in Hungary, the proportion of the small fraction is 50%; in Estonia, it is 54%; and in Austria, it is 68% (Faitli et al., 2019) (Bhatnagar et al., 2017). The prevalence of waste packaging (plastic, glass, paper, and metal) is considerably higher in European countries, which is the determining factor. As an illustration, the proportion of packaging in Austria is 15.0%, in Hungary it is 28.4%, and in Estonia it is 23.9% (Wolfsberger et al., 2015) (Bhatnagar et al., 2017), even while taking into account the prohibition on disposing of valuable components in landfills. The composition of combustible waste based on depth is presented in Table 10. The average values of combustible waste composition are shown in Figure 19.

Table 10. Composition of Combustible Waste in Each Depth

Depth (m)	**Composition of Combustile Waste (%)**								
	Zone 1			**Zone 2**			**Zone 3**		
	Plastic	Textile	Compost	Plastic	Textile	Compost	Plastic	Textile	Compost
0-1	53	19	28	44	8	49	23	7	71
1-2	45	0	55	32	7	61	23	6	71
2-3	64	2	34	34	28	39	25	11	64
3-4	25	2	74	24	25	50	10	2	89
4-5	24	3	73	31	9	60	19	15	66
5-6	41	10	49	27	2	72	8	2	91
6-7	16	2	82	26	2	72	10	3	87
7-8	40	3	57	22	3	75	29	10	60
8-9	25	0	75	14	0	86	15	5	80
9-10	35	4	60	26	7	67	1	0	99
10-11	29	2	69	13	2	86	18	1	81

Depth (m)	Composition of Combustile Waste (%)								
	Zone 1			Zone 2			Zone 3		
11-12	28	1	71	9	1	90	10	2	88
12-13	28	7	65	30	7	64	11	4	85
13-14	20	2	78	13	4	84			
14-15	20	0	79	21	4	74			
15-16	27	1	72	13	3	84			
16-17	17	2	82	5	0	95			
17-18	46	1	52						
Average	31	3	64	23	6	71	16	5	79

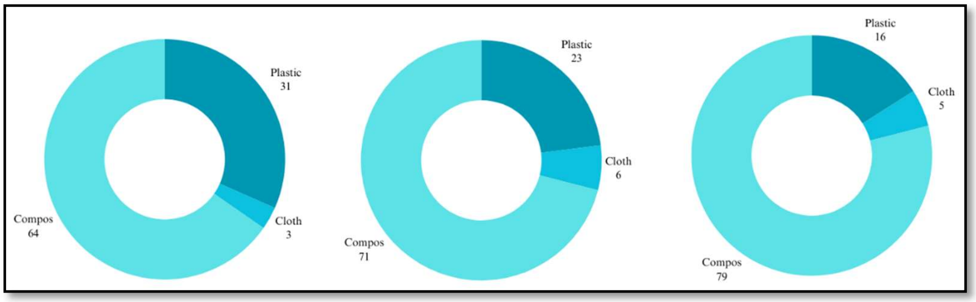

Figure 19. Composition of Combustible Waste (a) Zone 1 (b) Zone 2 (c) Zone 3

4.3.5 Calorific Value

The calorific value of plastic waste in Tamangapa landfill is 29,862 MJ/kg, this value has met European standards but when compared with the results of previous studies this value is still considered low. In other studies, obtained Low calorie values that may be due to other materials mixed and high-water content. In a separate study, Chiemchaisri et al. (2010) examined the possibility of utilizing plastic debris from excavated material as refuse-derived fuel (RDF). It was discovered that plastic, particularly plastic bags, has a high calorific value ranging from 27,5 to 38,5 MJ/kg. Table 11 shows the calorific value of textile waste is 19,945 MJ/Kg and the calorific value of the compost starts from 2,929 to 2,879 MJ/Kg.

Table 11. Calorific Value of All Materials in Landfill

Sample	Calorific Value (MJ/kg)
Zone 1	
Compost	2,879
Zone 2	
Compost	3,864
Zone 3	
Compost	2,929
Plastik in All Zone	29,862
Textile	18,945

4.3.6 Volume Waste in Landfill

The total volume of waste in landfill is 4.019.162.51 m^3, with the largest volume in Zone 3 being 1.695.535.8 m^3. Zone 3 is the largest area, with an area of 7.34 ha, and is still in use to this day. Next is zone 4, with a volume of 1.444.509,4 m^3. The area of zone 4 is 6.38 ha, and it is an inactive zone. The size and volume of waste in each zone are shown in detail in Table 12.

Table 12. The Volume of Waste in Each Zone

Zone	Volume of Waste (m^3)
Old Landfill	617.739,47
Zone 1	1.444.509,40
Zone 2	261.377,84
Zone 3	1.695.535,80
Total	4.019.162,51

4.4 Summary

This research shows that in landfill waste mining, the composition of plastic waste is the most dominant of the other waste materials. In Zone 1 (inactive zone), plastic waste contributed about 31% of the total waste in this old landfill area, including plastic bags and beverage bottles. Meanwhile, in location 2, about 22% of plastic waste was found, and in location 3, about 14%. Testing the calorie value of plastic waste after drying obtained an average result of 29.862 MJ/kg. The total potential volume of plastic waste in Tamangapa landfill is 742,676,05 m^3. Plastic waste found at these landfills has a variety of potentials but requires treatment processes to get maximum results.

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Chapter 5. Life cycle assessment of Biological Treatment Scenario of Municipal Solid Waste in Makassar, Indonesia.

5.1 Introduction

The challenge faced by developing countries in sustainable development is to create an efficient and economical waste management system. This is particularly applicable to urban waste, which is greatly influenced by the income level of the population, consumption patterns, and economic development (Khair et al., 2019; Marshall & Farahbakhsh, 2013; Otoniel et al., 2008). The implementation of sustainable development principles in waste management is exemplified through the utilization of a waste hierarchy, which encompasses a range of initiatives focused on preventing the generation of waste, promoting preparatory measures for reuse, actively engaging in recycling practices, facilitating recovery through alternative processes, and ensuring the appropriate disposal of non-recoverable waste.

Each technology can have a positive impact in one aspect while simultaneously having a negative impact in another. To assess, compare, analyses, evaluate, and estimate the environmental impact of a product, a systematic approach commonly used is the Life Cycle Assessment (LCA) method (Cellura et al., 2011). The LCA study on testing five scenarios of material recovery facility (MRF)/recycling, composting, incineration, landfilling, and collection shows that composting is the most environmentally sustainable approach for municipal solid waste management (MSWM) (Banar et al., 2009). Furthermore, other studies evaluated the effectiveness of composting and mechanical-biological treatment (MBT), and other management strategies. The study revealed that composting and MBT outperform incineration, landfilling, and other methods of waste management method (Mendes et al., 2004). In other research, a comparison was made between landfilling and alternative MSWM options. The result found that landfills have the highest global warming potential (GWP) among various waste management approaches due to higher emissions of methane and carbon dioxide (Dong et al., 2014; Zaman, n.d.). Aerobic Digestion (AD) processing has several advantages, including the ability to reduce the need for landfill space, generate a source of energy, and mitigate pollution (Evangelisti et al., 2014; Wilkie, 2005)

In developing countries such as Indonesia, the capacity of waste management systems still needs to be improved, primarily centered on landfilling practices. Only 41-42% of the total waste generated, approximately 61 million tons per year (Yuliani et al., 2022), is transported and disposed of in landfill sites. Most cities in Indonesia, like Makassar City, utilize open dumping methods in these landfill sites (Anggraini et al., 2021), resulting in environmental degradation and risks to human health during their operation. This study utilizes Life Cycle Assessment (LCA) to determine the environmental impacts of several waste treatment scenarios, focusing on biological processing. Various waste management methods include landfilling with or without energy recovery, composting, and anaerobic digestion.

5.2 Methods

The method used in this study is LCA manual calculation with spreadsheets. The stages of Life Cycle Assessment (LCA) consist of the following: determine goal and scope definition, system boundary determination, inventory analysis, life cycle impact assessment, and interpretation (Finnveden et al., 2009; Rebitzer et al., 2004). The present study employs the Life Cycle Assessment (LCA) methodology to compare and evaluate multiple biological treatment scenarios, aiming to identify a viable scenario for future implementation. The primary objective is to develop three alternative waste management scenarios specifically designed for MSW Makassar. The three scenarios encompass distinct waste management approaches, including landfilling, composting, and Anaerobic Digestion (AD). The current waste management practices at the Tamangapa Makassar Landfill include composting and landfilling. As part of alternative scenarios, Anaerobic Digestion (AD) is introduced as an additional waste management method.

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5.2.1 Goal and scope

The study aims to compare the environmental impact of biological treatment in three scenarios to choose the best scenario with minimum emissions for waste management in Makassar City in the future. The scope of this study includes the transportation of waste from its source, waste management by composting using the windrow composting method, and waste treatment with anaerobic digestion as an alternative approach.

5.2.2 System boundary

Based on the waste composition in Makassar, most of the waste consists of organic waste that can be biologically treated. This study is based on government policies, where 70% of the waste generated will be processed through composting and anaerobic digestion. The system boundary of this study is limited to the open windrow composting method, which covers the entire process from the shredding process, curing windrow tuners, screening and stabilization, and until the compost is ready to use (Figure 20).

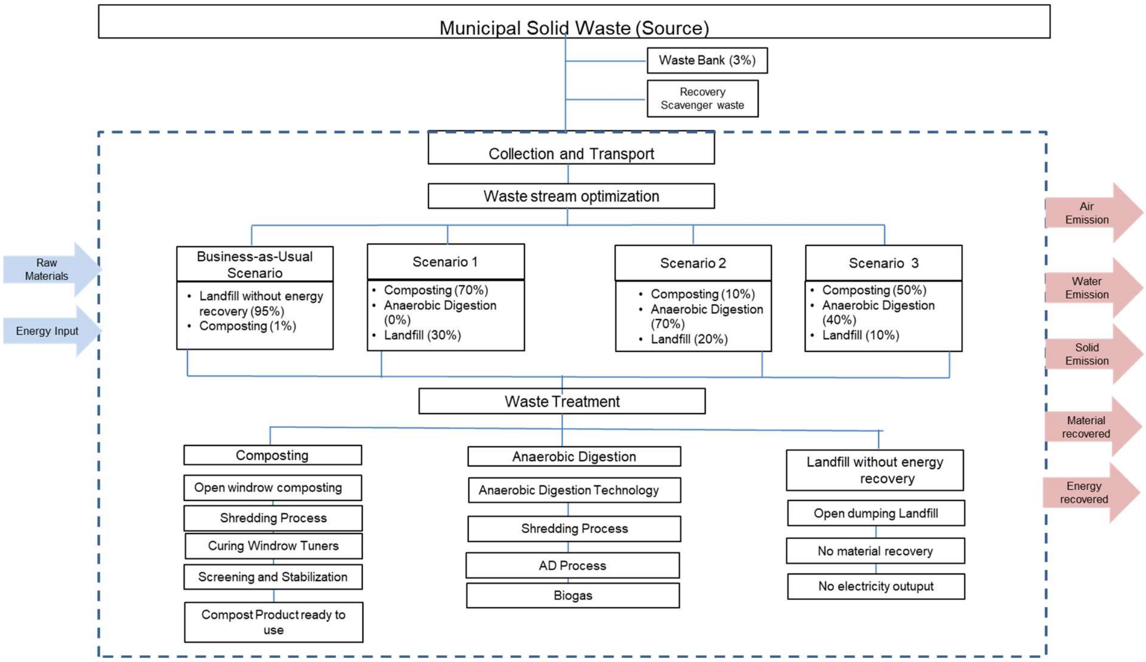

Figure 20. LCA system boundary

The application of compost outside the scope of this system is not considered. The anaerobic digestion process is limited to the shredding process, anaerobic digestion process, and until to produce biogas. As for landfill, the system employed is open dumping without energy recovery and electricity generation (based on existing conditions).

5.2.3 Scenario

The waste management scenarios consist of the Business as Usual (BaU) scenario, representing current waste management practices involving landfill and composting. Scenario 1 assumes 70% of waste to composting and 30% to landfill. Scenario 2 assumes 70% of the waste goes for Anaerobic Digestion, 10% for composting, and 20% for landfill. Scenario 3 assumes 50% of the waste goes for composting, 40% for Anaerobic Digestion, and 10% for landfill (Table 13). The scenario design considers several regulations in Indonesia, such as Presidential Regulation No. 83/2018 on marine debris prevention and Minister Regulation (MoEF) No. 75/2019 on waste roadmaps by producers (Mustafa et al., 2022), which promote the role of recycling and composting treatments.

Table 13. Scenario Assumed waste allocation for MSWM treatment in Makassar 2025

Scenario	Composting	Anaerobic Digestion	Landfill
1	70%	0	30%
2	10%	70%	20%
3	50%	40%	10%
BaU	1%	0	95%

5.3 Results and Discussions

5.3.1 Waste composition

The main composition of solid waste in developing countries, including Indonesia, primarily consists of waste materials that can naturally decompose, namely biodegradable waste. The municipal solid waste generated from developing countries primarily originates from households (55-80%), followed by market or commercial areas (10-30%) (Abdel-Shafy & Mansour, 2018).

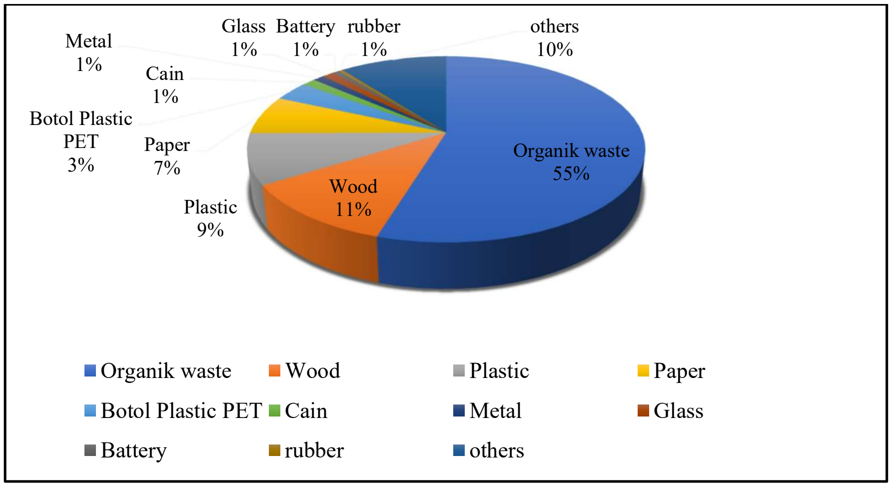

Figure 21. Waste composition.

Analysis of waste composition reveals that the category of waste that dominates in terms of proportion is as follows: biodegradable waste represents about 73% of the total, non-biological waste, including plastics, cane, rubber, and metals, account for about 26%, and hazardous waste such as batteries represent a small fraction of about 1%. Figure 21 illustrates the waste composition specifically observed at Makassar.

5.3.2 Inventory analysis.

Before the analysis, the waste generation data of the city of Makassar is projected for 2025, which is the target year for Jastranas (National Strategi Policy). Jastranas is a roadmap of government policy that applies nationally in the managing household waste and similar garbage. Jastranas has set a target by 2025, and waste management should reach 100%, with a 30% reduction of waste and 70% treatment of waste (*National Plastic Waste Reduction Strategic Actions for Indonesia*, n.d.). To forecast the amount of waste generation in 2025 using data time series population (2017-2021) and population growth rate, then multiplied by the average amount of waste generation in Makassar (Kawai & Tasaki, 2016). The projection method used is the geometric method. The result of the projections is calculated at 70% as the input data to be analyses.

Makassar produced 410,291 tons of waste in total in 2021, or average1,139 tons per day. The projected waste generation for 2025 is estimated to reach 440,955.13 tons per year, equivalent to 1,208 kg per person per day, considering an average population growth rate of 0.58%. Based on the national strategic policy for the year 2025, Indonesia has set targets to reduce waste by 30% and treatment by 70%, amounting to approximately 308,668.59 tons per year.

The data on emission factors and equivalence factors at the midpoint stages were obtained through information gathering from various relevant sources for this study. The data sources utilized include: the IPCC report conducted to obtain emission factors for waste transport vehicles (Eggleston, 2006a); the IPCC report for shredding emission factors; the IPCC report for composting and landfill emission factors (Eggleston, 2006b); the study conducted by Xu (Xu et al., 2015) for anaerobic digestion emission factors; the research by Diaz and Warith (Diaz & Warith, 2006) for heavy equipment emission factors.

The input data for waste processing per ton comes from resource use on transportation, composting, AD, and landfill operations. Each activity requires the input of resources such as fuel, water, and electricity in varying quantities. Specific details regarding the amount and volume of these resources can be found in Table 14.

Table 14. The resource input per ton of waste processed

Operation	Input/Ton	Resources
Transportation	5.48 L	Fuel
	2.17 L	Fuel
Composting	38.85 L	Water
	1.29 kWh	Electricity
AD	2.17 L	Fuel
	1,440 L	Water
Landfill	0.86 L	Heavy Equipment Diesel

The difference in the amount of garbage is based on the percentage of each scenario. The resources used in the composting process, such as fuel, electricity, and water match the need in terms of the amount of waste input. As well as on anaerobic digestion process, and resources on landfill activity. The type of power in each scenario can be seen in Table 15.

Table 15. Input Activity in Each Scenario

Input	BaU	Scenario 1	Scenario 2	Scenario 3
Waste for processing (kg)	308,668,594.73	308,668,594.73	308,668,594.73	308,668,594.73
Waste for compost (kg)	3,086,686	216,068,016	30,866,859	154,334,297
Fuel (shredding process) (L)	6,790.71	475,349.64	67,907.09	339,535.45
Water consumption (L)	120,072	84,050,458	12,007,208	60,036,042
Electricity (kWh)	4,105.29	287,370.46	41,052.92	205,264.62
Waste for AD (kg)	0	0	216,068,016	123,467,438
Fuel (shredding process) (L)	0	0	475,349.64	271,628.36
Water consumption for AD (L)	0	0	313,298,623.66	179,027,784.95
Waste to landfill (kg)	305,581,909	92,600,578	61,733,719	30,866,859
Fuel (landfill activity) (L)	1,200	364	242	121

5.3.3 Interpretation

The impact categories presented in this study are divided into three sections: namely global warming (GWP), acidification (AP), and eutrophication. The first step in conducting Life Cycle Impact Assessment (LCIA) is to categorize emissions into the selected impact categories (Leibrecht, 2006) Such as category CO_2, CH_4, N_2O, and CO are classified in the category of global warming. The next step is characterization process at the midpoint level. The characterization process is a quantitative measure to calculate a variety of emissions within an impact category, in this case using equivalency factors to ensure consistent units. As the impact of global warming are expressed in equivalence to GWP (kg CO_2eq), acidification (kg SO_2eq), and eutrophication (kg PO_4^3eq). The analysis results on existing BaU scenario showed the most significant impact on the GWP category of 8,436,685.61 kgCO_2eq; these emissions come from garbage transportation activities and landfill activity using heavy vehicles. In 3 other scenarios, scenario 1 GWP value of 2,512,671.78 kg CO_2eq yields a higher emission impact than scenario 2, 2,327,498.49 kg CO_2eq, and scenario 3 is 2,142,325.19 kgCO_2eq (Figure 3). Global warming increases in scenario 1 due to the composting process, which uses fuel to shred waste materials. Emission values in the global warming category were the lowest in scenario 3, where this scenario was waste treatment with an almost equal ratio between composting and AD, and the amount of garbage dumped into landfill was only 10%.

Acidification and eutrophication vary between scenarios because input values in the compounding process and AD differ in each scenario. The environmental impact category on acidification shows the most considerable value in scenario 1, at 302,893.48 kg SO2eq/year (Figure 22**)**. The lowest acidification category emissions in scenario 2 (46,072.48 kg SO_2eq/year) are from AD. In the eutrophication impact category, the highest value in scenario 1 is 101,808.21 kg PO_4^3eq/year, where the emission calculator comes from the compositing process. In this process, NH_3 in composition contributes to the environmental burden of eutrophication. The most negligible impact on the eutrophication category was in scenario 2 (27,259.43 kg PO_4^3eq/year), dominated by the AD waste process. The eutrophication load on the compounding process has a more significant impact than the AD process.

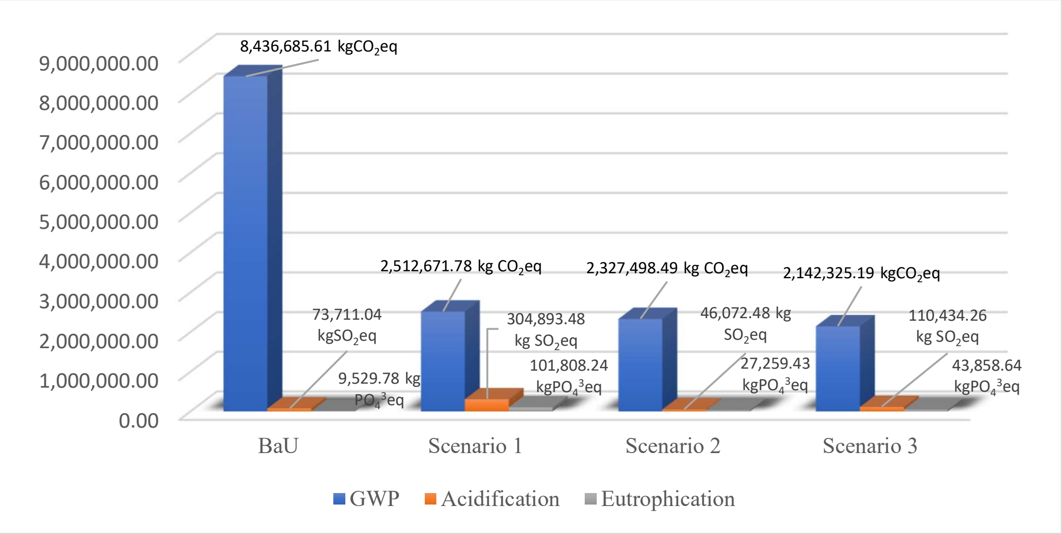

Figure 22. The emission value for each scenario

Among the scenarios considered, in scenario 1, most waste processing uses compost processes, showing high emissions in all impact assessment categories, both levels of global warming, absorption, and eutrophication. Scenario 2, where waste processing mostly on the AD process, showed high GWP values but the lowest of acidification and eutrophication, among other scenarios. Scenario 3, a combination of compost and AD, shows low global warming values but higher categories of acidification and eutrophication, where the contribution of emissions comes from the composting process. Scenario 3 was chosen as the optimal waste management approach among the evaluated scenarios. However, mitigation efforts are needed to minimize the emissions from the composition process by arranging the mixing and placing the cover on the pile during the compositing process.

5.4 Summary

This study shows the results of the LCA analysis on the environmental impact of emerging global warming, with scenario 3 showing the most minimal emissions. However, other impact categories, i.e., acidification and eutrophication, show high emission values origin from the composting process. This scenario is recommended as an optimal waste management approach from other scenarios.

Treatment is required to reduce the acidification and eutrophication emissions in the composting process, such as reducing the waste composting activity in the compositing process and providing a cover on compost stacks that can reduce NH_3 emissions.

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Chapter 6. Environmental Impact of Waste to Energy Scenario in Makassar, Indonesia

6.1 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 & 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 per capita per day to 1.2 kg per capita per day (Hoornweg & Bhada-Tata, 2012). Globally, the world produces 2.01 billion tons of urban waste annually, and it is predicted that by 2050, this amount will increase to 3.4 billion tons per year (Silpa 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 & 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 line with the Sustainable Development Goals (SDGs) agenda, mainly focusing on the goal of affordable and clean energy (SDG 7) among the 17 targeted goals, waste-to-energy (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 (Chand Malav et al., 2020), China (Themelis & 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 (Dezhen Chen & 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 No. 18/2008, which serves as the foundation for proper MSW management through the Reduce, Reuse, and Recycle (3R) program (Damanhuri et al., 2014). Subsequently, Presidential Regulation No. 97/2017, commonly known as Jakstranas, sets targets to reduce 30% of MSW and manage 70% of MSW by 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 waste-to-energy (WtE). This strategy is detailed in Government Regulation No. 79/2014, which aims to increase the share of new and renewable energy sources to 23% by 2025 (Mustafa et al., 2022). The government is increasingly focusing on incineration-based waste-to-energy (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). Therefore, a methodology is needed to evaluate the holistic environmental impact of various MSW systems. Life cycle assessment (LCA) is widely used as a methodology that considers the entire life cycle of a product or waste from cradle to grave, including 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 landfill gas (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.

6.2 Materials and Methods

6.2.1 Location of Studi

This research was conducted in Makassar City, located on Sulawesi Island in Indonesia. Figure 23 illustrates the map of Indonesia, with an 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, Makassar had a population of 1,432,189 people in 2022. 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.

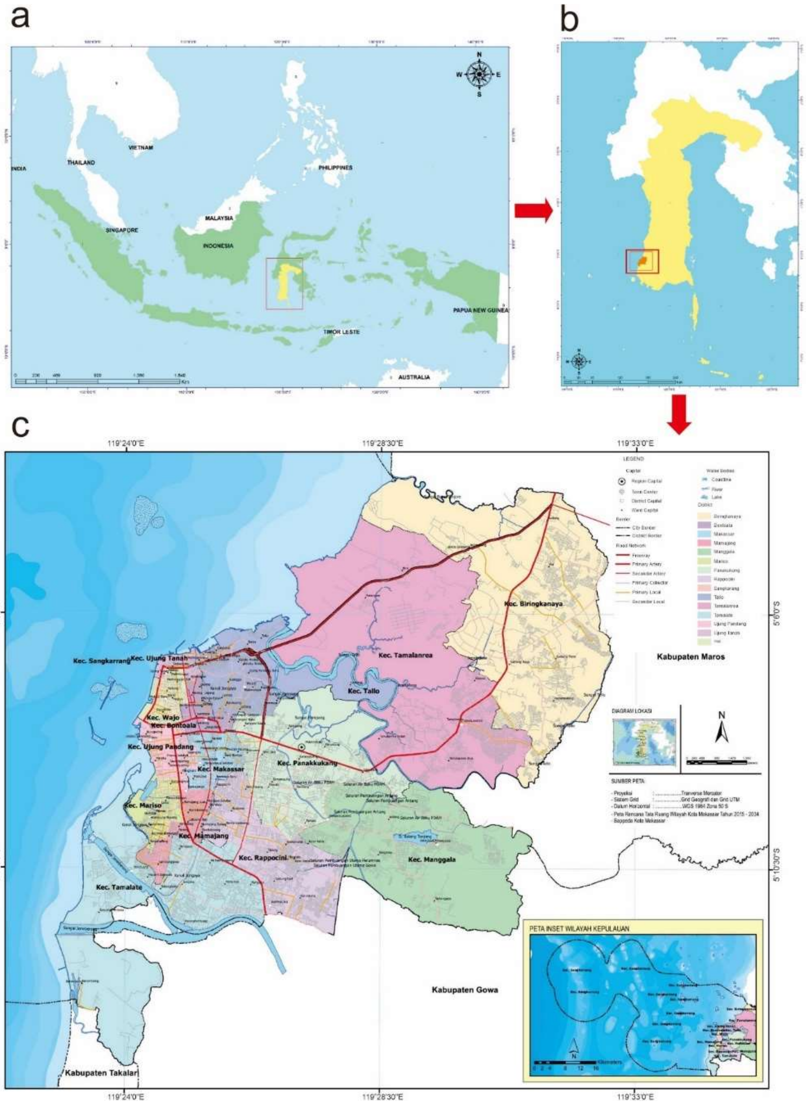

Figure 23. Lokasi Studi

6.2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool used to assess potential environmental impacts by calculating all emissions associated with various MSW 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. There are four stages in the LCA study: Goal and Scope Definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation. (Zegardło, 2021)

6.2.3 Goal and Scope

The LCA study aims to obtain appropriate model scenarios based on the environmental impacts of various Waste-to-Energy (WtE) treatments, including composting, incineration, and landfill gas (LFG) methods. The system boundary in this study (Figure 24) 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)

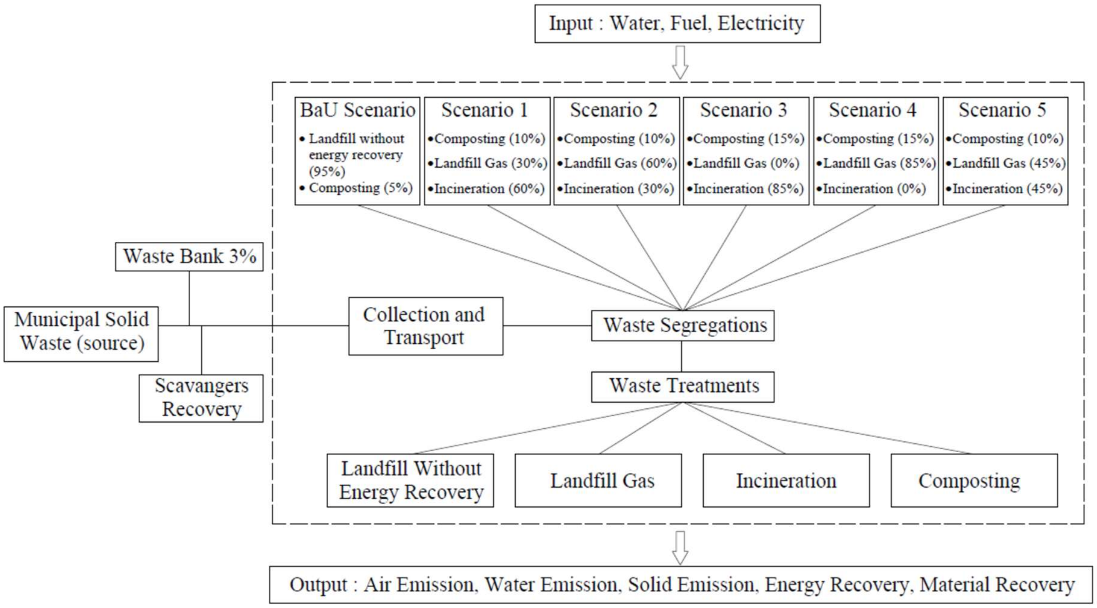

Figure 24. Boundary System

Figure 26 shows the System Boundary of the LCA Study from MSW transportation to the sorting facility and the preparation site according to the scenario. The input includes 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. Impact categories were selected for the Waste-to-Energy scenarios: Global warming potential (GWP) is based on CO_2, CH_4, and N_2O emissions.

6.2.4 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 16 are 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 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.

Table 16. 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%

6.2.5. Life Cycle Inventory

Waste composition.

Makassar is classified as a large 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/person/day. Figure 25 provides an overview of the waste composition 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.

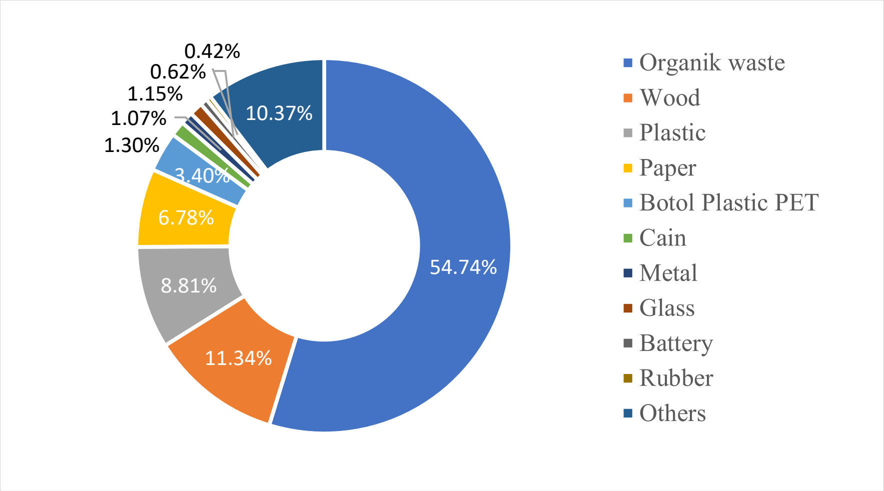

Figure 25. Waste Composition

Collection and Transport

The collection and transportation of MSW in Makassar City covers a total route length of 12,536.7 kilometers annually (figure 26). The number of trucks in operation is 319, distributed across 15 districts, each consuming 15 liters of diesel daily. 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.

The emissions from the collection and transportation activities to be calculated are CO_2 gas emissions and will be included in the BaU (Business as Usual) scenario.

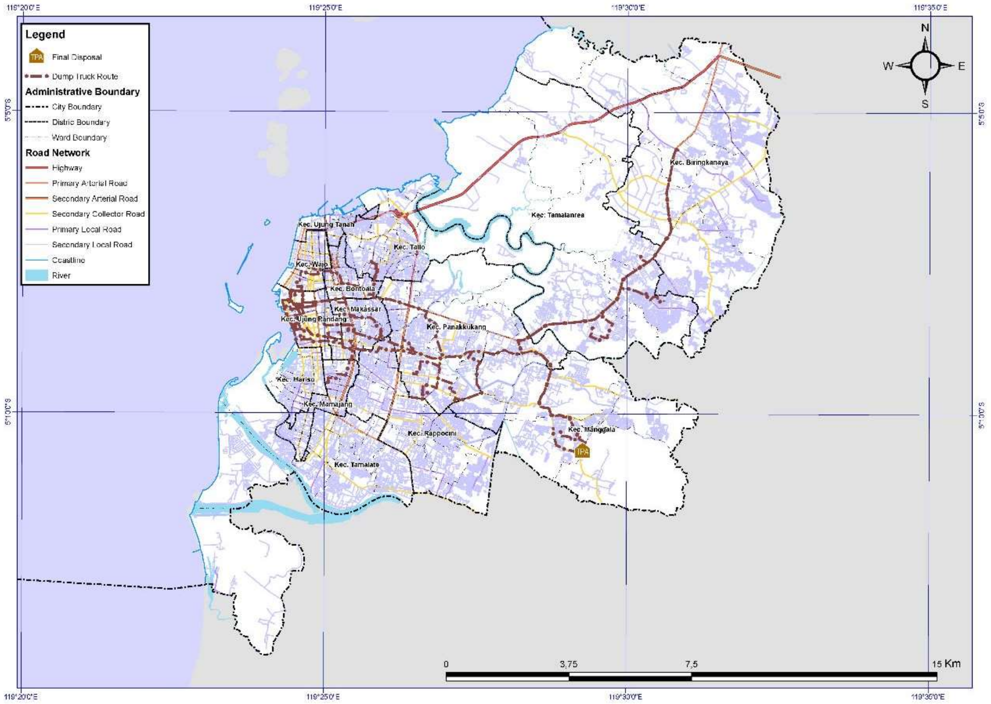

Figure 26. Waste Transport Rute

Solid Waste Disposal Site (SWDS) Tamangapa is located 15 km from the center 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 (Lando et al., 2021). The functional unit for calculating GHG emissions at a landfill without energy recovery is the amount of MSW per year (Mustafa et al., 2022). The year 2025 is used as a baseline with waste generation amounting to 440,955,135.34 kg per year. Figure 27 shows landfill activities at the Tamangapa landfill using an excavator. 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 (Service Office of Environment in Makassar City, 2022).

Figure 27. Landfill Activity

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 (NOx), and Carbon Monoxide (CO) (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.):

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

Where:

MSWT : Total MSW generated (Gg/yr.),
MSWF : Fraction of MSW disposed to solid waste disposal sites,
MCF : Methane correction factor (fraction),
DOC : Degradable organic carbon (fraction) (kg C/ kg SW),
DOCF : Fraction DOC dissimilated,
F : Fraction of CH4 in landfill gas (IPCC default is 0.5),
16/12 : 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 (IPCC, 2006). Under anaerobic conditions, composting generates CH_4, with less than 1% of CH_4 being released freely into the atmosphere (Arnold, 2005). Other emissions produced include N_2O, ranging from 0.5% to 5% (Detzel et al., 2003). The formulas used to calculate CH_4 and N_2O emissions from the composting process are as follows:

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

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)

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

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).

Emission factor for CH_4 and N_2O can be estimated using the default values in Table 17 for the biological treatment. Assumptions on the waste treated are estimated using wet waste.

Table 17. Emission Factors for CH_4 and N_2O Emissions from Biological Treatment of waste

Type of Biological Treatment	Default Emission Factors for CH_4 and N_2O Emissions from Biological Treatment of waste				
	CH_4 Emission factors (g CH_4/kg waste treated)		N_2O Emission factors (g CH4/kg waste treated)		Remarks
	On a dry weight basis	On a moist weight basis	On a dry weight basis	On a moist weight basis	Assumptions on the waste treated: 25-50% DOC in dry matter, 2% N in dry matter, moisture content 60%. The emission factors for dry waste are estimated from those for wet waste assuming a moisture content of 60% in 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 at biogas facilities	2	0,8	Assumed Negligible	Assumed Negligible	

Source: IPCC 2006

Incinerator

Incineration is the process of burning solid and liquid waste in a controlled facility. To achieve more complete combustion, the process 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 emissions such as CO_2, CH_4, and N_2O, with CO_2 emissions being more significant than those of CH_4 and N_2O (IPCC, 2006).

Metal conical, waste heat recovery, ram-feed, batch feed, and continuous feed are types of early generation incinerators (Stear, 1971). Next-generation incinerators use periodic waste combustion systems, allowing for more complete burning of waste with larger capacities (Makarichi et al., 2018). More advanced incinerator technologies sort waste based on its optical properties using optical devices (Brown, 2011). One type of incinerator capable of burning large amounts of waste without the need for sorting and shredding, except for household waste and hazardous materials, is the Moving Grate Incinerator (Wissing et al., 2017).

CO_2 and N_2O emissions from the incineration process can be calculated using the following formula:

CO_2 emissions (Gg/yr) = $\sum_i (SWi \bullet dmi \bullet CFi \bullet FCFi \bullet OFi) \bullet 44/12$ (4)

Where:

CO_2 : Emissions is CO_2 emissions in inventory year (Gg/yr),

SWi : Total amount of solid waste of type i (wet weight) incinerated (Gg/yr),

dmi : Dry matter content in the waste (wet weight) incinerated,

CFi : fraction of carbon in the dry matter (total carbon content), (fraction),

FCFi : fraction of fossil carbon in the total carbon, (fraction),

OFi : oxidation factor, (fraction), 44/12 is conversion factor from C to CO_2.

The formula of N_2O emissions (Gg/yr) = $\sum_i (IWi \bullet EFi) \bullet 10^{-6}$ (5)

Where:

N_2O Emissions : N_2O emissions in inventory year, Gg/yr,

IWi : amount of incinerated/open-burned waste of type i , Gg/yr,

EFi : N_2O emission factor (kg N_2O/Gg of waste) for waste of type i, 10^{-6} is conversion from kilogram to gigagram.

i : category or type of waste incinerated.

The components of MSW that can be processed in an incinerator include paper, textiles, food waste, wood, garden and park waste, nappies, rubber, and leather. The dry matter content as a percentage of the wet weight for each MSW component is presented in Table 18. Paper and wood have high DOC values when dry, with the highest carbon content found in plastic waste when dry, followed by rubber.

Table 18. Default Dry Matter Content, DOC Content, Total carbon Content and Fossil Carbon Fraction of Different MSW Components

MSW Component	Dry matter content in % of wet weight	DOC content in % of wet waste		DOC content in % of dry waste		Total carbon content in % of dry weight		Fossil carbon fraction in % 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 and Park 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

Landfill Gas

Landfill gas primarily comprises methane and carbon dioxide, with trace amounts of non-methane organic compounds. Effective management and utilization of LFG can significantly reduce greenhouse gas emissions and provide a renewable source of energy (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 (Chanton, J. P., et al., 2009). Proper design and maintenance of landfill gas collectors are essential to optimize gas recovery and minimize the release of methane into the atmosphere. (Cudjoe & Acquah, 2021)

6.3 Result and Discussion

Based on the Jakstranas 2025 waste management policy, LCA modeling is used to assess the environmental impacts of waste-to-energy scenarios in Makassar. LCA modeling is used to analyze the environmental impacts of waste-to-energy scenarios in Makassar City based on the Jakstranas 2025 waste management policy. Table 19 shows the environmental impact of the current situation (BaU scenario) regarding waste transportation routes and the use of heavy equipment in landfill activities. Table 20 presents CH_4 emissions in landfills with the open dumping method that is still currently used. In terms of the mass (kg) of impacts, it was found that GWP100 significantly contributes to environmental impacts where final waste disposal (without energy recovery) is predominant.

BaU

Table 19. CO_2 Emissions from Transportation and Excavation Activities

SWDS Activity	MSW (kg)	Distance (km)	Fuel (Liter)	EF Transport $kgCO_2$/km/ ton MSW	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

CO2 emissions in the BaU scenario are generated from transportation and excavation activities, totalling 84.762.975,36 kg/year.

Table 20. 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			

MSW Component	Percentage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH4 Generated Gg CH4/year
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

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, the CH_4 emissions from composting are 88.191,02 kg/year (table 21).

Table 21. CH_4 and N_2O Emissions from Composting Processes

Mi (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

Scenario 1.

In scenario 1, incineration reduces the mass of MSW by 219.357 Gg of solid waste per year. Based on table 22, the result shows this burning activity results in CO_2 emissions from the incinerator of 192.678.737 kg/year. The types of MSW that can be incinerated are organic waste, wood, plastic, paper, and textile. The CH_4 emissions from the incineration process amount to 43.871.494 kg/year (table 23).

Table 22. Estimation of CO_2 Emissions from Incineration of Waste

Type of waste	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
MSW :					1	3,667		
Organic	144,72	0,40	0,38				80,65	
Wood	29,97	0,85	0,50				46,71	
Plastic	23,28	1,00	0,75	1,00			64,02	
Paper	17,93	0,90	0,46	0,01			0,27	
Textile	3,43	0,80	0,50	0,20			1,00	
Total	219,35			1,21			192,67	192.678.737

a* Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)

b* Dry Matter Content dm (fraction)
c* Fraction of Carbon in Dry Matter CF (fraction)
d* Fraction of Fossil in Dry Matter FCF (fraction)
e* Oxidation Factor OF (fraction)
f* Conversion Factor
g* Fossil CO_2 Emissions (Gg CO_2/year)

Table 23. Estimation of CH_4 Emissions from Incineration

Type of waste	Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)	Methane Emission Factor (kg CH4/Gg Wet Waste)			Methane Emission (Gg CH4/year)		
		Type Incineration/Technology			Type Incineration/Technology		
		Continues	Semi-Continues	Batch	Continues	Semi-Continues	Batch
		Stoker	Stoker	Stoker	Stoker	Stoker	Stoker
organic	144,721	0,2	6	60	28,944	8,683E-04	8,683E-03
wood	29,976				5,995	1,799E-04	1,799E-03
plastic	23,282				4,656	1,397E-04	1,397E-03
paper	17,938				3,588	1,076E-04	1,076E-03
Textile	3,439				0,688	2,064E-05	2,064E-04
Total	219,357				43,871	1,316E-03	1,316E-02
					43871494,860	1316,145	13161,448

Table 24. Estimation of CH_4 Emissions from Landfill Gas

MSW Component	Percentage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH4 Generated Gg CH4/year	LFG Collection (Gg CH4/year) Moderate 71%	Fugitif Emission (Gg CH4/year) Moderate
Organic Waste	54,70%	72.360.737,654	15%	196,35	117,812	83,646	34,165
Wood	11,33%	14.988.065,039	43%	24,15	14,489	10,287	4,202
Plastic	8,80%	11.641.215,564					
Paper	6,78%	8.969.027,446	40%	8,04	4,827	3,427	1,400
Pet bottle	3,40%	4.497.742,377					
Textile	1,30%	1.719.725,027	24%	0,18	0,106	0,076	0,031
Metal	1,07%	1.415.465,983					
Glass	1,15%	1.521.295,216					
Battery	0,62%	820.176,551					
Rubber	0,42%	555.603,470					
Others	10,36%	13.704.885,596					
Total					137,234	97,436	39,798

The CH_4 emissions that cannot be captured in the gas collection facility are released into the atmosphere. In scenario 1, the amount of CH4 gas released into the atmosphere is 39,798 Gg/year (table 24).

Table 25. Estimation of N_2O Emissions from Incineration of Waste

Type of waste	Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)	Nitrous Oxide Emission Factor (kg N2O/ Gg Wet Waste)			Nitrous Oxide Emission (N2O Gg/year)	
		Type Incenerator/Technology			Type Incenerator/Technology	
		continues-semi continues		Batch	continues-semi continues	Batch
		50		60		
organic	144,721				7236,0716	8683,2859
wood	29,976				1498,8060	1798,5673
plastic	23,282				1164,1212	1396,9454
paper	17,938				896,9025	1076,2830
Textile	3,439				171,9725	206,3669
Total					10967,8737	13161,4485

Table 25 shows the total N_2O emissions from waste incineration activities amount to 10967,87 Gg/year.

Scenario 2.

In scenario 2, where landfill gas is 60%, incineration is 30%, and composting is 10%, the results show the CO_2 emissions from the incineration process amount to 96.339 Gg/year (table 26). Meanwhile, the other gases produced are CH_4 and N_2O, with amounts of 21.935.747,43 kg CH_4/year (table 27) and 5.483,93 kg N_2O/year, respectively (table 28).

Table 26. Estimation of CO_2 Emissions from Incineration of Waste

Type of waste	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
MSW :					1	3,667		
Organic	72,361	0,400	0,380				40,329	
Wood	14,988	0,850	0,500				23,356	
Plastic	11,641	1,000	0,750	1,000			32,013	
paper	8,969	0,900	0,460	0,010			0,136	

Textile	1,720	0,800	0,500	0,200			0,504	
Total	109,679			1,210			96,339	96.339.368

a* Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)
b* Dry Matter Content dm (fraction)
c* Fraction of Carbon in Dry Matter CF (fraction)
d* Fraction of Fossil in Dry Matter FCF (fraction)
e* Oxidation Factor OF (fraction)
f* Conversion Factor
g* Fossil CO_2 Emissions (Gg CO_2/year)

Table 27. Estimation of CH_4 Emissions from Incineration of Waste

Type of waste	**Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)**	**Methane Emission Factor (kg CH4/Gg Wet Waste)**			**Methane Emission (Gg CH4/year)**		
		Type Incineration/Technology			Type Incineration/Technology		
		Continues	Semi-Continues	Batch	Continues	Semi-Continues	Batch
		Stoker	Stoker	Stoker	Stoker	Stoker	Stoker
organic	72,361	0,2	6	60	14,47	4,342E-04	4,342E-03
wood	14,988				3,00	8,993E-05	8,993E-04
plastic	11,641				2,33	6,985E-05	6,985E-04
paper	8,969				1,79	5,381E-05	5,381E-04
Textile	1,720				0,34	1,032E-05	1,032E-04
Total	109,679				2,194E+01	6,581E-04	6,581E-03
					21935747,430	658,072	6580,724

Table 28. Estimation of N_2O Emissions from Incineration of Waste

Type of waste	**Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)**	**Nitrous Oxide Emission Factor (kg N2O/ Gg Wet Waste)**		**Nitrous Oxide Emission (N2O Gg/year)**	
		Type Incenerator/Technology		**Type Incenerator/Technology**	
		continues-semi continues	**Batch**	**continues-semi continues**	**Batch**
		50	60		
organic	72,361			0,00362	0,00434
wood	14,988			0,00075	0,00090
plastic	11,641			0,00058	0,00070
paper	8,969			0,00045	0,00054
Textile	1,720			0,00009	0,00010
Total				0,00548	0,00658
(kg N2O/year)				5483,936858	6580,72423

In scenario 2, the amount of MSW processed in the gas collection installation is 60% of the total MSW entering the SWDS. Table 29 shows the amount of CH_4 gas captured is 348.375.247,32 kg CH_4/year, while the amount released into the atmosphere is 142.294.115,10 kg CH_4/year.

Table 29. Estimated Emsission CH_4 from landfill Gass

MSW Component	Percentage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH4 Generated Gg CH4/year	LFG Collection (Gg CH4/year) Moderate 71%	Fugitif Emission (Gg CH4/year) Moderate
Organic Waste	54,70%	144.721.475,30	15%	785,41	471,24	334,58	136,66
Wood	11,33%	14.988.065,03	43%	24,15	14,48	10,28	4,20
Plastic	8,80%	11.641.215,56					
Paper	6,78%	8.969.027,44	40%	8,04	4,82	3,42	1,40
Pet bottle	3,40%	4.497.742,37					
Textile	1,30%	1.719.725,02	24%	0,18	0,10	0,07	0,03
Metal	1,07%	1.415.465,98					
Glass	1,15%	1.521.295,21					
Battery	0,62%	820.176,55					
Rubber	0,42%	555.603,47			0,00	0,00	0,00
Others	10,36%	13.704.885,59					
Total					490,669	348,375	142,294

Scenario 3

The incinerator activity in scenario 3 results in CO_2 emissions of 278.496.513 kg CO2/year (table 30). Additionally, table 31 and 32 shows emissions of CH_4 and N_2O are 6.215 Gg CH_4/year and 0.015 Gg N_2O/year, respectively.

Table 30. Estimation of CO_2 Emissions from Incineration of Waste

Type of waste	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
MSW:					1	3,667		
organic	205,02	0,400	0,380				114,27	
wood	42,47	0,850	0,500				66,18	
plastic	32,98	1,000	0,750	1,000			90,70	
paper	25,41	0,900	0,460	0,010			0,39	
Textile	4,87	3,898	0,500	0,200			6,96	
Total	310,756	7,048	2,590	1,210			278,497	278.496.513

a* Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)
b* Dry Matter Content dm (fraction)
c* Fraction of Carbon in Dry Matter CF (fraction)
d* Fraction of Fossil in Dry Matter FCF (fraction)
e* Oxidation Factor OF (fraction)
f* Conversion Factor
g* Fossil CO2 Emissions (Gg CO2/year)

Table 31. Estimation of CH_4 Emissions from Incineration of Waste

Type of waste	Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)	Methane Emission (Gg CH4/year)	
		Type Incinerator/Technology	
		Continues Incineration	
		Stoker	Fluidised bed
Organic	205,022	4,100E-05	
Wood	42,466	8,493E-06	
Plastic	32,983	6,597E-06	
paper	25,412	5,082E-06	
Textile	4,873	9,745E-07	
Total	310,756	6,215E-05	

Table 32. Estimation of N_2O Emissions from Incineration of Waste

Type of waste	Total Amount of waste Incinerated (wet weight) (GgWaste/ year)	Nitrous Oxide Emission Factor (kg N_2O/ Gg Wet Waste)		Nitrous Oxide Emission (N_2O Gg/year)	
		Type Incinerator/Technology		Type Incinerator/Technology	
		continues-semi continues	Batch	continues-semi continues	Batch
		50	**60**		
Organic	205,022			0,01025	0,01230
Wood	42,466			0,00212	0,00255
Plastic	32,983			0,00165	0,00198
paper	25,412			0,00127	0,00152
Textile	4,873			0,00024	0,00029
Total				0,01554	0,01865
(kg N_2O/year)				15537,82	18645,38

Table 33. Estimation of CH_4 and N_2O Emissions from Composting

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)
66,143	4	0,24	0,2646	0,01587

Table 33 shows composting process, CH_4 and N_2O emissions are produced in small amounts, specifically 0.264 Gg CH_4/year and 0.0158 Gg N_2O/year. In scenario 3, the percentage of waste handled in the gas collection installation (flare) is 0%, so there is no CH_4 gas captured or released into the atmosphere.

Scenario 4

In scenario 4, there are no CO_2, CH_4, and N_2O emissions from incineration. However, from the gas collection activities, 685.284 Gg CH_4/year is captured, while 279.905 Gg CH_4/year is released into the atmosphere (table 34).

Table 34. Estimation of CH_4 Emissions and Capture from LFG

MSW Component	Percentage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH_4 Generated Gg CH4/year	LFG Collection (Gg CH_4/year) Moderate 71%	Fugitive Emission (Gg CH_4/year) Moderate
Organic Waste	54,70%	205.022.090,018	15%	1.576,277	945,766	671,494	274,272
Wood	11,33%	14.988.065,039	43%	24,149	14,489	10,287	4,202
Plastic	8,80%	11.641.215,564					
Paper	6,78%	8.969.027,446	40%	8,044	4,827	3,427	1,400
Pet bottle	3,40%	4.497.742,377					
Textile	1,30%	1.719.725,027	24%	0,177	0,106	0,076	0,031
Metal	1,07%	1.415.465,983					
Glass	1,15%	1.521.295,216					
Battery	0,62%	820.176,551					
Rubber	0,42%	555.603,470			0,000	0,000	0,000
Others	10,36%	13.704.885,596					
					965,189	685,284	279,905

The emissions from composting consist of 0.2646 Gg/year of CH_4 and 0.01587 Gg/year of N_2O (table 35).

Table 35. Estimation of CH_4 and N_2O Emissions from Composting of Waste

Mi (Gg/year)	EF CH_4 (g CH4/kg waste treated)	EF N_2O (g CH4/kg waste treated)	CH_4 Emissions (Gg/year)	N_2O Emissions (Gg/year)
66,143	4	0,24	0,2646	0,01587

Scenario 5

In scenario 5, the amount of CO_2 emissions generated from the incineration process is 144,509,052 kg CO_2/year (table 36). Additionally, table 37 and 38 shows the emissions of CH_4 and N_2O are 32,094 Gg CH_4/year and 8,938.488 kg N_2O/year, respectively.

Table 36. Estimation of CO_2 Emissions from Incineration of Waste

Type of waste	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
MSW :					1	3,667		
Organic	108,54	0,40	0,38				60,49	
Wood	22,48	0,85	0,50				35,03	
Plastic	17,46	1,00	0,75	1,00			48,02	
paper	13,45	0,90	0,46	0,01			0,20	
Textile	2,58	0,80	0,50	0,20			0,76	
Total	164,51	3,95	2,59	1,21			144,50	144.509.052

a* Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)
b* Dry Matter Content dm (fraction)
c* Fraction of Carbon in Dry Matter CF (fraction)
d* Fraction of Fossil in Dry Matter FCF (fraction)
e* Oxidation Factor OF (fraction)
f* Conversion Factor
g* Fossil CO2 Emissions (Gg CO2/year)

Table 37. Estimation of CH_4 Emissions from Incineration of Waste

Type of waste	Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)	Methane Emission Factor (kg CH4/Gg Wet Waste)			Methane Emission (Gg CH4/year)		
		Type Incineration/Technology			Type Incineration/Technology		
		Continues	Semi-Continues	Batch	Continues	Semi-Continues	Batch
		Stoker	Stoker	Stoker	Stoker	Stoker	Stoker
organic	108,541	0,2	6	60	2,171E-05	6,512E-04	6,512E-03
wood	22,482				4,496E-06	1,349E-04	1,349E-03
plastic	17,462				3,492E-06	1,048E-04	1,048E-03
paper	13,454				2,691E-06	8,072E-05	8,072E-04
Textile	2,580				5,159E-07	1,548E-05	1,548E-04
Total	164,518				3,290E-05	9,871E-04	9,871E-03
					32,904	987,109	9871,086

Table 38. Estimation of N_2O Emissions from Incineration of Waste

Type of waste	Total Amount of waste Incinerated (wet Weight) (Gg Waste/year)	Nitrous Oxide Emission Factor (kg N2O/ Gg Wet Waste)		Nitrous Oxide Emission (N2O Gg/year)	
		Type Incenerator/Technology		Type Incenerator/Technology	
		continues-semi continues	Batch	continues-semi continues	Batch
		50	60		
organic	108,541			0,00543	0,00651
wood	22,482			0,00112	0,00135
plastic	17,462			0,00087	0,00105
paper	25,412			0,00127	0,00152
Textile	4,873			0,00024	0,00029
Total				0,00894	0,01073
(kg N2O/year)				8938,488566	10726,18628

The LFG in the form of CH_4 captured by the gas collection installation is 201.994.187,75 kg/year (table 39), while the amount released into the atmosphere is 82.504.668,23 kg.

Table 39. Estimation of CH_4 Emissions and Capture from LFG

MSW Component	Percen-tage	Amount (kg/year)	DOC content in % of wet waste	DDOcm Gg/Year	CH_4 Generated Gg CH4/year	LFG Collection (GgCH4/year) Moderate 71%	Fugitive Emission (Gg CH4/year) Moderate
Organic Waste	54,70%	108.541.106,480	15%	441,794	265,076	188,204	76,872
Wood	11,33%	14.988.065,039	43%	24,149	14,489	10,287	4,202
Plastic	8,80%	11.641.215,564					
Paper	6,78%	8.969.027,446	40%	8,044	4,827	3,427	1,400
Pet bottle	3,40%	4.497.742,377					
Textile	1,30%	1.719.725,027	24%	0,177	0,106	0,076	0,031
Metal	1,07%	1.415.465,983					
Glass	1,15%	1.521.295,216					
Battery	0,62%	820.176,551					
Rubber	0,42%	555.603,470					
Others	10,36%	13.704.885,596					
				Total	284,499	201,994	82,505

Table 40 shows the composting process, small amounts of CH_4 and N_2O are produced, specifically 0.1764 Gg CH_4/year and 0.01058 Gg N_2O/year.

Table 40. Estimation of CH_4 and N_2O Emissions from Composting of Waste

Mi (Gg/year)	EF CH_4 (g CH4/kg waste treated)	EF N2O (g CH4/kg waste treated)	CH_4 Emissions (Gg/year)	N_2O Emissions (Gg/year)
44,096	4	0,24	0,1764	0,01058

Environmental Impact of All scenarios

The open dumping and landfilling activities at the Tamangapa SWDS result in significant emissions of CO_2, CH_4, and N_2O (8.48 E+07 kg CO2/year, 1.38 E+09 kg CH_4/year, and 5.29 E+03 kg N_2O/year).

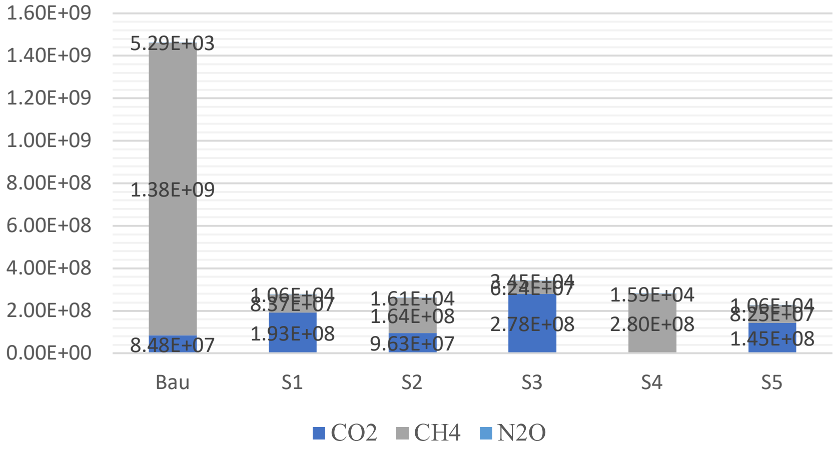

Figure 28. Life cycle environmental impact of WtE scenarios in 2025

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, CH4, and N_2O emissions are recovered. 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 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 CH4 gas that cannot be contained by the LFG Collector.

Electricity Generation from Incineration and LFG Collector.

Table 41. Electricity Generation from Incineration

$W_{total\ (Ton/day)}$	Waste	W_i (Tons/day)	p (%)	$W_{scincineration}$ (Tons/day)	$FW_{scincineration}$ (Kg/day)	$LCVW_{incineration}$ (kJ/Kg)	P (kW)	$E_{incineration}$ (kWh/year)	E_{actual} (kWh/year)
1,208,096	Organic	661	54,70	396	328,20	3.088.027	2.820.592	18.210.079	16.206.970
	Wood	137	11,33	82	67,98	430.067			
	Plastic	106	8,80	64	52,80	2.096.050			
	Paper	82	6,78	49	40,68	577.372			
	Pet Botol	41	3,40	25	20,40				
	Cain	16	1,30	9	7,80	140.488			
	Metal	13	1,07	8	6,42				
	Glass	14	1,15	8	6,90				
	Battery	7	0,62	4	3,72				
	Rubber	5	0,42	3	2,52	53.841			
	Other	125	10,36	75	62,16				
	Total	1.207		724	599,58	6.385.845			

Table 42. Electricity Generation from LPG

Q_{waste}	$Q_{waste(LF)annual}$	Q_{CH4} (m^3/year)	$Cap_{CH4(t)}$ (m3/year)	$E_{actual\ (LFG)}$ (kWh/year)
1.760.522.439.900	6,42591E+14	2.105.637	1.579.228	4.369.328

6.4 Summary

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 plays a crucial role in reducing the concentration of CH_4 in the atmosphere due to its facility for capturing CH_4 gas.

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Chapter 7. Conclusion

1. The bibliometric analysis results offer valuable insights into waste-to-energy research. This study reviewed and mapped scientific literature on waste-to-energy (WTE) in developing countries. Screening the Scopus database yielded 116 relevant articles. The analysis generated keyword clusters, with the highest occurrence related to "Municipal Solid Waste" in one cluster. Another cluster showed an increasing occurrence of keywords related to "technology," indicating a technological trend in waste-to-energy methods like incineration, anaerobic digestion, pyrolysis, and composting. "Life cycle assessment" emerged as the most utilized method for assessing environmental impacts. Research trends indicate that global waste-to-energy research began in 1978, but research specific to developing countries started in 2004 and has since grown significantly. Visualization of research trends highlights keywords such as biofuel and electricity, indicating current research focuses on waste-to-energy.
2. The waste management situation in Makassar, Indonesia, poses several challenges and opportunities for improvement. The city has implemented waste management regulations, including Law No. 18 of 2008 on Waste Management and Regional Regulation No. 4 of 2011 on Solid Waste Management. Following the waste hierarchy approach, these regulations emphasize waste reduction, reuse, and recycling. Makassar City's waste management system involves direct collection and transportation to the final waste processing site. The waste transportation system utilizes various methods, including the Hauled Container System (HCS) and the Stationary Container System (SCS), focusing on door-to-door waste collection to improve efficiency. The Tamangapa landfill, the city's primary waste disposal site, faces capacity issues and lacks proper leachate management, posing environmental and health risks. To address these challenges, the city must improve its waste management infrastructure, enhance public awareness and

participation in waste reduction and recycling, and explore sustainable waste treatment technologies, such as Waste-to-Energy (WtE) facilities. Collaborative efforts between the government, private sector, and community are crucial to achieving sustainable waste management in Makassar City.

3. Investigating the potential of landfill waste in Makassar, found the significant presence of plastic waste in landfill waste mining activities. Plastic waste, including items such as plastic bags and beverage bottles, was found to be the most dominant waste material, comprising 31% of the total waste in Zone 1 (inactive zone) of the old landfill area. In Zone 2, plastic waste accounted for about 22% of the waste, and in Zone 3, approximately 14%. Calorific value testing of dried plastic waste yielded an average result of 29,862 MJ/kg. The total potential volume of plastic waste in the Tamangapa landfill is estimated at 742,676.05 m3. While plastic waste presents various potentials, it requires proper treatment processes to achieve maximum benefits.
4. Life Cycle Assessment (LCA) was conducted to analyze the environmental impact of emerging global warming from the biological treatment scenario of Municipal Solid Waste (MSW) in Makassar. Scenario 3, which combines composting and Anaerobic Digestion (AD), demonstrated the most minor emissions. However, other impact categories, such as acidification and eutrophication, showed high emission values originating from the composting process. Scenario 3 is recommended as the optimal waste management approach compared to other scenarios. Treatment methods are necessary to reduce acidification and eutrophication emissions in the composting process, such as minimizing waste composting activity and covering compost stacks to reduce NH3 emissions.
5. 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 CO2 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 plays a crucial role in reducing the concentration of CH4 in the atmosphere due to its facility for capturing CH4 gas.

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