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Waste to Energy Utilization Technology Study in Padang City

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ABSTRACT

Solid waste management in Padang City is problematic due to the annual increase in waste generation, which leads to various environmental issues. This study aims to predict the most profitable waste-to-energy (WtE) treatment methods from technical and environmental perspectives that can alleviate these issues in Padang City. The study begins with analyzing solid waste generation, composition, and characteristics. Additionally, the amount of incoming waste for thermal planning is projected based on projected generation and population. The environmental implications were assessed using the LCA (Life Cycle Assessment) method. Various waste treatment methods' technical and environmental viability was evaluated, focusing on projected waste generation in 2031, estimated at 929 tons/day. The analysis of technical aspects revealed that thermal processing of mixed waste gasification is the most profitable option, requiring only 5,101 m^2 of land and capable of producing 188 GWh/year while achieving the lowest LCA Single Score of 5.82E+04 Conversely, anaerobic digesters and RDF processing generate 120 GWh and 47 GWh of electrical energy, respectively, with Single Score LCA of 4.25E+10 Pt and 7.74E+09 Pt. However, the environmental impact of WtE is the most significant, primarily due to its contribution to global warming. Global warming is predominantly attributed to carbon monoxide (CO) compounds, with carbon dioxide (CO_2) being the primary emission responsible for the observed increase in global temperature.

Keywords: *Anaerobic Digester; Gasification; LCA; RDF; Waste to Energy (WtE).*

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INTRODUCTION

The city of Padang is classified as a big city. In 2020, its population reached 973,152 people, divided into 11 sub-districts [1]. The amount of waste managed at the Final Processing Site (TPA) is 500 tons/day [2]. It should be noted that urban growth and development are increasing trends in urban centers, and urban solid waste generation, especially domestic solid waste, shows the exact correlation with this development. As a result, managing this solid waste is becoming an increasingly significant challenge, requiring effective strategies to address this environmental problem. This difference poses significant challenges, especially if solid waste management practices do not match the characteristics of the waste produced. Failure to do so can lead to various environmental problems. Integrating technological solutions and technological advances is essential for effective solid waste management.

Among the available technologies is the waste-to-energy (WtE) conversion process. This technology involves processing waste into energy, which can be reused for various purposes, including building operations or for use by the community as an alternative energy source. This technology includes a variety of advanced methodologies capable of converting residual materials generated from post-recycling processes into valuable products and chemicals, including ethanol, biodiesel, and clean renewable energy sources. Examples of well-known

WtE conversion technologies include Refuse Derived Fuel (RDF), Anaerobic Digester (AD), and Gasification. Waste-to-energy, referred to as waste-to-energy power plants (PLTSa) in Indonesia, is one form of renewable energy development. As outlined in Law Number 30 of 2007 concerning Energy, the national energy policy is based on environmentally friendly energy principles, and bioenergy is recognized as a renewable energy source in Indonesia [3]. However, the realization of the WtE project until December 2013 shows that the development of WtE is still far from the maximum when viewed from the existing potential. Based on data from The Institute for Essential Services Reform (IESR) and The Carbon Trust, WtE, which has been operating until the end of 2013, has only produced 93.5 MW [4].

Life Cycle Assessment (LCA) assesses the environmental impact of a product, process, or activity throughout its life cycle. The LCA method used is following the ISO 14040:2016 standard. According to ISO 14040:2016, the LCA analysis process consists of four distinct stages: setting objectives and describing the scope, compiling inventory data (inputs and outputs) throughout the life cycle (LCI), calculating potential environmental impacts (LCIA), and interpreting LCA results and providing recommendations for improvement [5]. The use of LCA in various research has played an important role in facilitating effective municipal waste management. It allows for the assessment of alternative waste management systems and facilitates identifying areas needing potential improvement [6].

Comprehensive research on each WtE technology, namely Refuse Derived Fuel (RDF), Anaerobic Digester (AD), and Gasification, is needed to ensure their effectiveness in reducing solid waste, increasing energy generation capacity, optimizing land requirements, and conducting Life Cycle Assessment (LCA) analysis. The findings of this study will provide important information to determine the WtE process and facilitate the development of environmentally friendly WtE applications.

The objectives of this study are to analyze the solid waste generation in Padang City, to analyze each Waste to Energy (WtE) technology in terms of its potential to reduce solid waste generation, the potential energy produced, the area of land required, and the Life Cycle Assessment (LCA) analysis; and to analyze the amount of solid waste entering or being processed at the Final Processing Site (TPA), to extend the service life of the TPA and reduce the need for TPA land.

METHOD

Data Collection

Data collection consists of foreground data and background data. Foreground data is collected by conducting interviews with the environmental service and field observations. Observations are conducted to observe the composition of solid waste entering the landfill. Interviews are conducted with the Padang City Environmental Service to obtain relevant data.

Background data were obtained from previous research relevant to the research topic, books, journals, and the SimaPro database. Background data consists of the calculation of energy produced by AD technology based on Kausar's research in 2016 [7] and de Laclos'es research in 1997 [8]. Calculation of land area required by AD technology based on Setiawan's research in 2017 [9]. Calculation of gasification technology based on Rachim's research in 2017 [10] and Wibowo's research in 2007 [11]. Emissions from the use of AD technology obtained from Huang's research in 2015 for 1 ton of waste processed [12] Emissions from the use of RDF and gasification technology obtained from the Department for Environment, Food and Rural Affairs (DEFRA) report in 2004 for 1 ton of waste processed [13]. Emissions from sanitary

CIVED Journal of Civil Engineering and Vocational Education
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landfill landfills obtained from the SimaPro database for the Rest of the World (RoW) region [14] and Saheri's research in 2017[15].

Solid Waste Generation Analysis

Solid waste generation analysis is carried out using secondary data that has been obtained and projected so that it can be initial data to determine the amount of waste that enters the WtE processing. To predict the amount of waste generation in an area, the following equation can be used [16]:

$$Qn = Qt\,(1+Cs)^{n} \quad (2.1)$$

With:

$$Cs = \frac{\left[1+\frac{C_i+C_p+C_{qn}}{3}\right]}{[1+p]} \quad (2.2)$$

Description:

Qn = solid waste generation in the next n years.
Qt = waste generation in the initial year of calculation.
Cs = increase/growth of the city.
Ci = growth rate of the industrial sector.
Cp = growth rate of the agricultural sector.
Cqn = rate of increase in per capita income.
P = population growth rate.

LCA Framework

LCA analysis was conducted following SNI ISO 14040:2016. According to the aforementioned standard, the LCA analysis is divided into four sequential steps: first, goal and scope definition; second, inventory analysis; third, environmental impact assessment; and fourth, interpretation [5].

Goal and Scope Definition

Goal and scope definitions are essential. It will be considered when the research results are interpreted, and it involves choices that determine data collection and how the system is modeled and assessed [6].

Some of the things to consider when defining the objective and scope are defining the functional unit, covering the product system, selecting the assessment parameters, selecting the geographical and temporal boundaries and setting of the study and the level of technology relevant to the processes in the product system, deciding on the relevant perspective, and identifying the need for a critical review [6].

Life Cycle Inventory (LCI)

This analysis examines all processes identified as part of the product system, and their flows are scaled according to the defined product reference flow of the functional unit. Inventory analysis often relies on common data for many processes derived from a database. The inventory analysis results from the Life Cycle Inventory, a list of quantified physical base flows for the product system associated with providing the service or function described by the functional unit [6].

EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Impact Assessment

The inventory analysis data will be used to assess potential environmental impacts. [6]. EDIP 2003 and Cumulative Energy Demand (CED) are the environmental impact assessment methods. Environmental impact assessment is conducted in four stages: impact classification, impact characterization, impact normalization, and weighting.

Impact Classification

Classification aims to organize and combine the inventory analysis results into impact categories**. Table 1** contains the environmental impact categories using the EDIP 2003 and CED methods.

Table 1. Classification of EDIP 2003 Impacts and Cumulative Energy Demand

No	**Impact Classification**	**Unit**
EDIP 2003		
1	Global Warming Potential (GWP100a)	Kg CO_2 eq
2	Ozone Formation (Vegetation)	m^2.ppm.h
3	Ozone Formation (Human)	person.ppm.h
4	Acidification	m^2
5	Terrestrial Eutrophication	m^2
6	Aquatic Eutrophication	kg N
7	Human Toxicity Air	person
8	Human Toxicity Water	m^3
9	Human Toxicity Soil	m^3
10	Ecotoxicity Water Chronic	m^3
11	Ecotoxicity Soil Chronic	m^3
Cumulative Energy Demand (CED)		
1	Non-Renewable Energy	MJ
2	Renewable Biomass	MJ

Impact Characterization

Impact characterization in LCA signifies the phase in which the life cycle inventory (LCI) findings are calculated into potential indicators of environmental impacts. At this stage, the types of emissions and resource use identified in the LCI are associated with specific environmental impact categories.

Impact Normalization

Normalization is when the impact characterization results are compared with reference or baseline values. Normalization aims to provide a perspective on the magnitude of environmental impacts generated by a product or process compared to the total environmental impact in a specific region or scale. Impact normalization is achieved by multiplying characterization results by the normalization factor. Table 2 provides information on the normalization factor utilized.

Weighting / *Single Score*

Weighting is the stage where the normalized impact results are compared with the weighting value of each impact. The objective of weighting is to provide a value that can be compared between each scenario. The weighting process involves the multiplication of normalization results by the weighting factor. Table 2 provides a comprehensive overview of the weighting factors employed in this study.

Table 2. Normalization Factors and Weighting Factors of EDIP 2003

No	Impact Classification	Normalization Factor	Weighting Factor
1	Global Warming Potential (GWP100a)	1.29E-04	1.1
2	Ozone Formation (Vegetation)	1.68E-05	1.2
3	Ozone Formation (Human)	3.52E-01	1.2
4	Acidification	2.54E-03	1.3
5	Terrestrial Eutrophication	7.30E-04	1.2
6	Aquatic Eutrophication	1.20E-01	1.4
7	Human Toxicity Air	2.11E-09	1.1
8	Human Toxicity Water	2.12E-05	1.3
9	Human Toxicity Soil	1.24E-04	1.2
10	Ecotoxicity Water Chronic	2.73E-07	0
11	Ecotoxicity Soil Chronic	1.37E-05	0

Interpretation constitutes the culminating phase in the LCA analysis. At this juncture, an evaluation of the environmental impact assessment is conducted. This analysis involves a comparative evaluation of the environmental impacts generated by the project.

WtE Technology Selection Analysis

The comparative analysis of WtE technologies was carried out based on several main factors, including the amount of waste that can be processed, the energy produced, the land area required, the amount of labor required, and the results of the LCA analysis. This assessment is presented as a weighting scheme to facilitate the selection of the most suitable technology for WtE in Padang City. The assessment was conducted using a weighting system that assigns values from 1 to 5 for the five technologies being compared. The weighting methodology is outlined as follows:

a. Amount of waste processed
   The highest value is determined by how much solid waste each technology processes. The waste with the highest processing capacity is assigned a value of 5, while the waste with the lowest processing capacity is assigned a value of 1. The weighting criteria are outlined in Table 3.

Table 3. Assessment Criteria Based on the Amount of Processed Solid Waste

Amount of Solid Waste (ton/day)	Value
< 600	1
600-700	2
701-800	3
801-900	4
> 900	5

b. Energy produced
   The maximum energy output of each technology determines the maximum attainable score. The technology with the highest energy output is assigned a value of 5, while the technology with the lowest waste production is assigned a value of 1. The weighting criteria are delineated in Table 4.

Table 4. Assessment Criteria Based on the Amount of Energy Produced

Energy Produced (GWh/year)	Value
< 50	1
50-100	2
101-150	3
151-200	4
> 200	5

Journal of Civil Engineering and Vocational Education
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http://cived.ppj.unp.ac.id/index.php/CIVED

c. Land area required
The highest value is attributed to the smallest or most effective land area, which requires minimal land area for processing. The smallest land area is assigned a value of 5, while the largest land area is assigned a value of 1. The weighting criteria can be found in Table 5.

Table 5. Assessment Criteria Based on Land Area Required

Land Area Required (m^2)	Value
< 10,000	5
10,000-20,000	4
20,001-30,000	3
30,001-40,000	2
> 40,000	1

d. Single score Life Cycle Assessment
The highest value is determined by the least potential impact, which is regarded as effective and, thus, environmentally friendly. The assessment assigns a value of 5 to the scenario with the smallest single score and a value of 1 to the scenario with the most significant single score. The basis for scoring utilizes the class interval formula, expressed as follows:

$$I = \frac{N_b - N_k}{n} \quad (2.3)$$

Description:
I = Class Interval
Nb= Biggest value
Nk= Lowest value
n = number of classes
The class interval results are subsequently adjusted to the number of classes. The weighting criteria can be found in Table 6.

Table 6. Assessment Criteria Based on Single Score LCA

Single Score LCA	Value
< 8.51E+09	5
8.51E+09 – 1.70E+10	4
1.70E+10 – 2.55E+10	3
2.55E+10 – 3.40E+10	2
> 3.40E+10	1

RESULTS AND DISCUSSION

Analysis of Solid Waste Generation Projection

Waste generation projection requires waste generation data for Padang City. This study uses existing research to project waste generation in Padang City. The calculation of waste generation units in Padang City was obtained from waste generation unit data in 2019, which were 3.707 l/o/h and 0.661 kg/o/h. The waste generation projection was then calculated and presented in Table 7.

Journal of Civil Engineering and Vocational Education
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Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Table 7 Projection of Solid Waste Generation

No	Year	Population (person)	Solid waste generation (l/p/day)	Solid waste generation (kg/p/day)	Solid waste generation (m^3/day)	Solid waste generation (ton/day)
1	2021	975,775	3.863	0.689	3,769	672
2	2022	988,014	3.943	0.703	3,896	694
3	2023	1,000,253	4.025	0.717	4,026	718
4	2024	1,012,492	4.109	0.732	4,160	741
5	2025	1,024,732	4.194	0.748	4,298	766
6	2026	1,036,971	4.281	0.763	4,439	791
7	2027	1,049,210	4.370	0.779	4,585	817
8	2028	1,061,449	4.460	0.795	4,735	844
9	2029	1,073,688	4.553	0.812	4,888	871
10	2030	1,085,927	4.647	0.828	5,047	900
11	2031	1,098,166	4.744	0.846	5,210	929

WtE Scenario Analysis

Refuse Derived Fuel (RDF)

RDF is a solid waste management technique that changes solid waste into something useful, namely fuel. RDF is produced from the mechanical separation of combustible and non-combustible fractions [17]. Solid waste generation data is based on household and similar solid waste generation data in Padang City in 2031 of 929 tons/day or 338,927 tons/year. Analysis of solid waste generation and composition data allows the determination of waste composition in Padang City. The potential for Padang City waste to be processed into RDF can be calculated using these data, as illustrated in Table 8. The RDF Scenario overview can be seen in Figure 1.

Table 8 Potential for RDF Processing in Padang City

Parameter	Composition (%)	Solid waste generation (ton/day)	TPA Service (%)	Component RDF (ton/day)
Food waste	32.92	306	80	245
Yard waste	25.12	233		187
Paper waste	13.17	122		98
Plastic waste	13.68	127		102
Metal/Cans	3.15	29		-
Textiles	2.65	25		20
Rubber/Leather	2.39	22		18
Glass	1.33	12		-
Other	5.59	52		42
Total		929		710

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Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

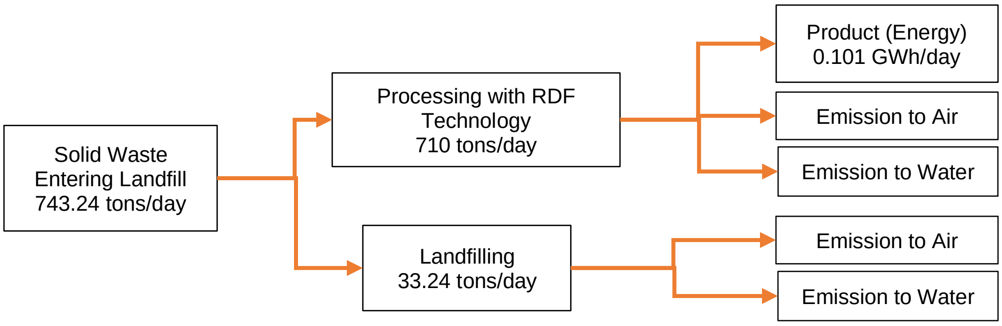

Figure 1. Solid Waste Processing Scenario with RDF

The assumption is that by 2031, 80% of Padang City's waste will be sent to the landfill, which means that the waste will be processed using RDF. Waste components that can be used as raw materials for RDF include waste that is easily combustible and has a high calorific value, such as plastic, paper, wood, textiles, and rubber/leather waste. Of the five types of waste, the potential generation that can be generated for RDF is 710 tons/day.

Table 9 Energy Produced by RDF

No.	**Solid Waste Composition**	**HHV**		**Energy Produced**	
		MJ/kg	**Ton/h**	**MJ**	**kWh**
1	Food waste	19.4	-	-	-
2	Yard waste	17.5	187	3,272,500	11,781,000
3	Plastic waste	42.6	102	4,345,200	15,642,720
4	Paper waste	17.4	98	1,705,200	6,138,720
5	Textiles	19.9	20	398,000	1,432,800
6	Rubber/Leather	40.4	18	727,200	2,617,920
7	Mixture waste	22.4	-	-	-
	Total		**424**	**10,448,100**	**37,613,160**

Based on the data presented in Table 9, the energy that can be produced based on the potential of waste that can be processed using the RDF method is 37,613,160 kWh or 37 GWh. RDF technology is also characterized by the need for quite a large amount of land, which is caused by the large volume of waste required by the bio-drying process. A comprehensive analysis of land requirements can be seen in Table 10.

Table 10 Land Area Required for RDF

No	**Zone**	**System**	**Land area required (m^2)**
1	A	Receiving and Feeding System □ Weighing, special area for sorted solid waste □ Receiving Hopper □ Feeding Conveyor	18,000
		Separation System □ Manual sorting conveyor □ Storage Bin Solid Waste Preparation System □ Shredder	

		Separation System □ 1st Trommel (50 mm) □ 2nd Tromel (20 mm) Feeding System to Storage Feeding conveyor	
2	B	Sistem Pengeringan □ Windrow	20,000
3	C	Management Facilities	10,800
		Car Parking Zone	
Total			**48,800**

Anaerobic Digestion (AD)

Making biogas using a biodigester creates an airtight system with the main parts consisting of a digester tank, a raw material input channel, a slurry output channel, and a biogas distribution hole that is formed. Several types of biogas reactors are often used [18].

The solid waste processed into biogas consists of organic vegetable and fruit waste from household kitchens. The amount of organic waste processed into biogas reaches 539 tons every day. Research by Paska in 2021 has determined the total solid content (TS%) value of organic vegetable and fruit waste at 20% and the potential for biogas production at 0.50 m^3 [19]. The components of AD waste are depicted in Table 11. The AD Scenario illustration can be seen in Figure 2.

Table 11. Potential for AD Processing in Padang City

Parameter	**Composition (%)**	**Solid waste generation (ton/day)**	**TPA Service (%)**	**Component AD (ton/day)**
Food waste	32.92	306	80	245
Yard waste	25.12	233		187
Paper waste	13.17	122		-
Plastic waste	13.68	127		-
Metal/Cans	3.15	29		-
Textiles	2.65	25		-
Rubber/Leather	2.39	22		-
Glass	1.33	12		-
Other	5.59	52		-
Total		929		432

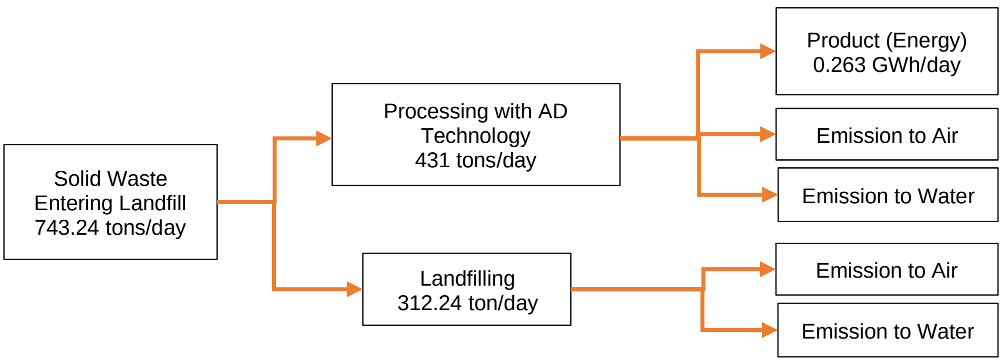

Figure 2. Solid Waste Processing Scenario with AD

CIVED Journal of Civil Engineering and Vocational Education
EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

The calculation results show that the land area needed for the anaerobic digester unit is 37,736 m^2, with a gas production capacity of 1,296,000 m^3/month. The energy value of 1 m^3 of biogas is equivalent to 6.1 kWh of electrical energy, which shows that the potential for generating electrical energy is around 263,520 kWh/day or 96 GWh/year.

Gasification

In general, gasification design requires pre-treatment in the form of shredding to reduce the size of the solid waste entering the reactor. In addition, a drying process is also needed to obtain a higher calorific value from dry solid waste. The next step is determining the machines and equipment needed for the thermal processing process. In this design, the machines needed are a crane, a shredder, a dryer, and gasifiers equipped with conveyor belts, furnaces, boilers, hydraulic ash discharge, water and tar cyclones, and air fans and generators. There are five main types of gasification units, namely vertical fixed bed, horizontal fixed bed, fluidized bed, multiple hearth, and rotary kiln. The three most commonly used units are vertical fixed bed, horizontal fixed bed, and fluidized bed [20].

The calculation of land requirements for a mixed solid waste gasification plant is shown in Table 12. The overview of the gasification scenario can be seen in **Figure 3**. In addition to materials, data is also entered in the Heat/Electricity column. Natural gas/LNG is selected as the electricity source. The amount of electricity required is calculated by multiplying the electricity requirements of each device by the amount of incoming waste in 2031. The results show that the amount of electricity required is 57,805.4 kWh/day.

Table 12. Gasification Land Requirements

No	Tools	Land Requirements (m^2)
1	Ramp	300
2	Raw material bunker	225
3	Crane	-
4	Shredder	468
5	Dryer	588
6	Gasifier	3,520
Total		5,101

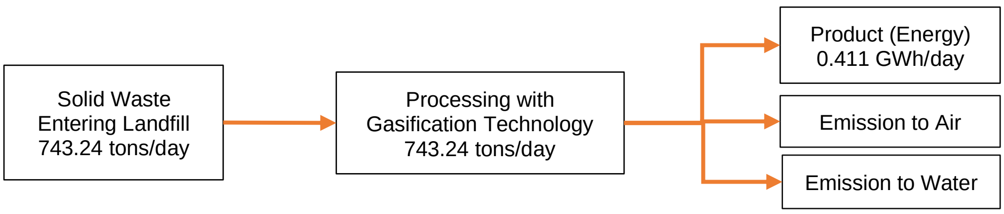

Figure 3. Scenario of Solid Waste Processing with Gasification

The output of the thermal processing is then calculated in terms of gas emissions, residual solids, and electricity. The residual solids are assumed to be used as construction materials, while the gas emissions are calculated in the LCA process. The electrical energy produced is around 148 GWh/year.

AD + RDF

AD and RDF technologies are planned to process wet and dry waste. AD technology is used for wet solid waste, and RDF technology is used for dry solid waste. Based on calculations, AD technology can process 431 tons/day of wet waste. At the same time, RDF technology can

EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

process 710 tons/day of mixed waste. So, the dry waste that RDF will process is 279 tons/day. The illustration of the combined gasification and RDF scenario can be seen in Figure 4.

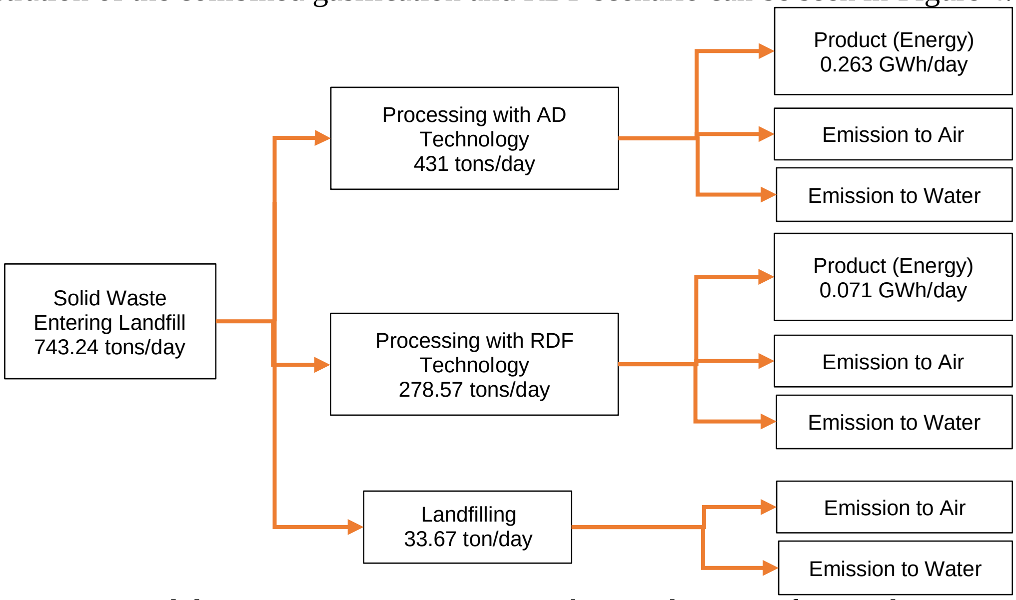

Figure 4. Solid Waste Processing Scenario with a Combination of AD and RDF

Based on the calculation, the energy produced by RDF processing dry solid waste is 70,367.78 kWh. At the same time, AD can produce 263,520 kWh. Thus, when combined, the energy produced by these two technologies is 122 GWh. The land area used is assumed to be the same as the previous calculation. The solid waste processed by RDF is reduced to 40% of the previous processing, so the land for RDF is assumed to be 40% of 48,800 m^2, which is 19,520 m^2. So, the land area is 57,266 m^2.

Gasification + AD

AD and gasification technology are planned to process wet and dry solid waste. Wet solid waste is processed with AD, and dry solid waste is processed by gasification. Based on calculations, AD technology can process 431 tons/day of wet solid waste. At the same time, gasification technology can process 743 tons/day of mixed solid waste. So, the dry solid waste that will be processed with gasification is 312 tons/day. The illustration of the combined gasification and AD scenario can be seen in Figure 5.

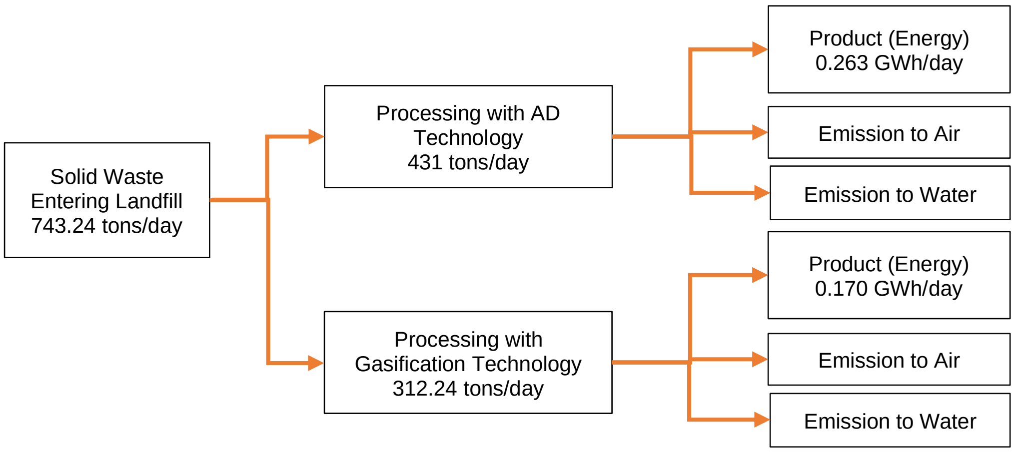

Figure 5. Solid Waste Processing Scenario with a Combination of AD and Gasification

EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Based on the calculation, the energy produced from processing dry solid waste by gasification is 169,808 kWh. At the same time, AD can produce 263,520 kWh. Thus, the total energy produced reaches 158 GWh/year. Waste processed by gasification is reduced to 42% of the previous processing, so the land for gasification is assumed to be 42% of 5,101 m^2, or 2,040 m^2. So, the land area when these two technologies are used together becomes 39,786 m^2.

WtE Life Cycle Assessment Analysis

Goal and Scope Definition

The objectives are determined by identifying the reasons for conducting LCA on WtE technology in Padang City. This LCA aims to calculate the potential environmental impacts of 5 WtE technology scenarios and provide recommendations for WtE technology with the most minor potential environmental impact.

The scope provides a clear picture of what will be analyzed, how the analysis will be conducted, and to what extent the results can be applied or compared. The scope of this study consists of functional units and system boundaries. The functional unit used in this study is 271,282.14 tons of solid waste entering the landfill.

The system boundaries in this study use gate-to-grave assessment. Gate-to-grave assessment is carried out from the solid waste entry into the Air Dingin TPA until the waste is dumped. The system boundaries in this study are shown in Figure 6.

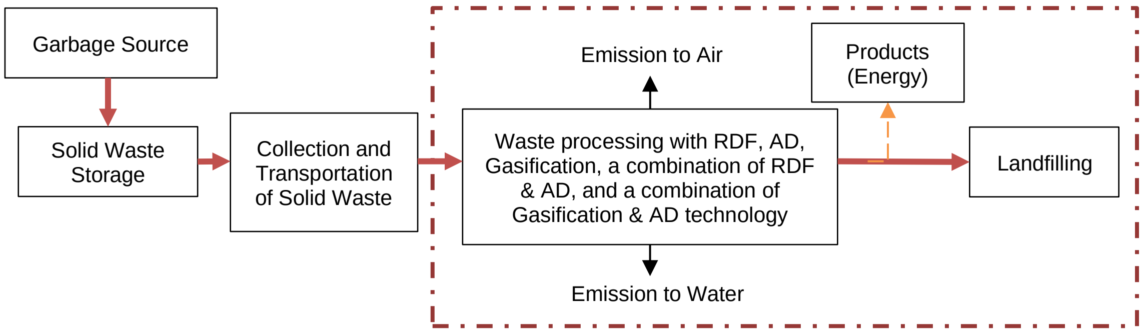

Figure 6. WtE LCA System Boundaries

Life Cycle Inventory (LCI)

Data in LCA analysis is called inventory data. At this stage, inventory data will be analyzed according to the functional units that have been determined, namely 271,282.14 tons of solid waste. The inventory analysis results, starting from materials, raw materials, energy consumption, and emissions, are shown in Table 13.

Tabel 13. Life Cycle Inventory Analysis

Proses	Parameter	Amount	Unit
Scenario 1 (RDF)			
1. RDF Process			
input	Solid waste generation	271,282.14	ton
	Electricity	50,452,516.42	kWh
output	Unprocessed solid waste	116,624.19	ton
	Energy generated	10,448,100.00	MJ
	Emissions to air		
	NOx	1.12E+04	kg
	SO_2	4.33E+03	kg
	HCl	1.86E+02	kg

CIVED Journal of Civil Engineering and Vocational Education

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Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Proses	Parameter	Amount	Unit
	HF	6.19E+01	kg
	PCDF	6.19E+03	kg
	CO_2	2.80E+07	kg
	CO	1.12E+04	kg
	CH_4	6.36E+04	kg
	NH_3	1.86E+04	kg
	HC	5.57E+03	kg
	Emissions to water		
	NH_3	2.47E+04	kg
	N	1.55E+03	kg
	SO_4	7.73E+02	kg
	COD	8.20E+04	kg
2. Landfill Process and Heavy Equipment			
input	Solid waste generation	116,624.19	ton
	BBM Excavator	4,835.86	L
	BBM Bulldozer	3,430.56	L
output	Emission to air		
	NOx	1.77E+10	kg
	Particulate	3.13E+02	kg
	SO_2	2.41E+09	kg
	HCl	5.12E+07	kg
	HF	5.36E+06	kg
	VOC	3.37E+04	kg
	Cd	2.19E+03	kg
	Ni	1.14E-02	kg
	Hg	4.08E-04	kg
	CO_2	1.61E+12	kg
	CO	1.30E+02	kg
	CH_4	8.05E+10	kg
	NH_3	1.64E+02	kg
	HC	3.92E+07	kg
	Emission to water		
	NH_3	5.78E+09	kg
	N	5.41E+09	kg
	COD	2.78E+10	kg
Scenario 2 (AD)			
1. AD process			
input	Solid waste generation	271,282.14	ton
output	Unprocessed solid waste	181,976.06	ton
	Energy generated	346,265,280.00	MJ
	Emissions to air		
	NOx	1.81E+04	kg
	Particulate	4.77E+03	kg
	SO_2	1.03E+04	kg
	HCl	6.77E+03	kg
	HF	2.33E+03	kg
	Cd	3.35E+01	kg
	Ni	1.01E+02	kg
	As	1.67E+02	kg
	Hg	2.01E+02	kg

Journal of Civil Engineering and Vocational Education
EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Proses	Parameter	Amount	Unit
	CO_2	1.81E+06	kg
	CO	2.74E+03	kg
	CH_4	6.06E+03	kg
	NH_3	1.70E+03	kg
	H_2S	1.44E+03	kg
	NMHC	6.94E+02	kg
2. Landfill Process and Heavy Equipment			
input	Solid waste generation	181,976.06	ton
	BBM Excavator	7,545.69	L
	BBM Bulldozer	5,352.93	L
output	Emission to air		
	NOx	2.77E+10	kg
	Particulate	4.89E+02	kg
	SO_2	3.77E+09	kg
	HCl	7.99E+07	kg
	HF	8.37E+06	kg
	VOC	5.26E+04	kg
	Cd	3.42E+03	kg
	Ni	1.78E-02	kg
	Hg	6.37E-04	kg
	CO_2	2.51E+12	kg
	CO	2.03E+02	kg
	CH_4	1.26E+11	kg
	NH_3	2.57E+02	kg
	HC	6.11E+07	kg
	Emission to water		
	NH_3	9.03E+09	kg
	N	8.44E+09	kg
	COD	4.33E+10	kg
Scenario 3 (Gasification)			
input	Solid waste generation	271,282.14	ton
	Electricity	92,046,031.23	kWh
output	Unprocessed solid waste	0	ton
	Energy generated	531,278,949.46	MJ
	Emissions to air		
	NOx	1.06E+05	kg
	Particulate	1.63E+03	kg
	SO_2	2.44E+03	kg
	HCl	4.34E+03	kg
	HF	2.94E+01	kg
	VOC	8.14E+02	kg
	Cd	4.70E-01	kg
	Ni	5.44E+00	kg
	As	1.49E+01	kg
	Hg	4.62E+00	kg
	PCDF	1.18E-06	kg
	CO_2	1.90E+08	kg
	CO	5.29E+03	kg
Scenario 4 (AD + RDF)			
1. Proses AD+RDF			

Journal of Civil Engineering and Vocational Education
EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Proses	Parameter	Amount	Unit
input	Solid waste generation	271,282.14	ton
	Electricity	50,452,516.42	kWh
output	Unprocessed solid waste	27,318.11	ton
	Energy generated	356,713,380.00	MJ
	Emissions to air		
	NOx	6.71E+04	kg
	Particulate	1.30E+04	kg
	SO_2	3.51E+04	kg
	HCl	1.88E+04	kg
	HF	6.46E+03	kg
	Cd	9.15E+01	kg
	Ni	2.76E+02	kg
	As	4.58E+02	kg
	Hg	5.48E+02	kg
	PCDF	9.76E+03	kg
	CO_2	4.91E+07	kg
	CO	2.51E+04	kg
	CH_4	1.17E+05	kg
	NH_3	3.39E+04	Kg
	H_2S	3.93E+03	kg
	NMHC	1.90E+03	kg
	HC	8.78E+03	kg
	Emission to water		
	NH_3	3.90E+04	kg
	N	2.44E+03	kg
	SO_4	1.22E+03	kg
	COD	1.29E+05	kg
2. Landfill Process and Heavy Equipment			
input	Solid waste generation	27,318.11	ton
	BBM Excavator	1,132.75	L
	BBM Bulldozer	803.58	L
output	Emission to air		
	NOx	4.15E+09	kg
	Partikulat	7.34E+01	kg
	SO_2	5.65E+08	kg
	HCl	1.20E+07	kg
	HF	1.26E+06	kg
	VOC	7.89E+03	kg
	Cd	5.14E+02	kg
	Ni	2.67E-03	kg
	Hg	9.56E-05	kg
	CO_2	3.77E+11	kg
	CO	3.04E+01	kg
	CH_4	1.88E+10	kg
	NH_3	3.85E+01	kg
	HC	9.18E+06	kg
	Emission to water		
	NH_3	1.35E+09	kg
	N	1.27E+09	kg
	COD	6.50E+09	kg

Proses	Parameter	Amount	Unit
Scenario 5 (AD + Gasification)			
input	Solid waste generation	271,282.14	ton
	Electricity	61,744,477.75	kWh
output	Unprocessed solid waste	0	ton
	Energy generated	702,647,199.30	MJ
	Emissions to air		
	NOx	1.61E+05	kg
	Particulate	1.61E+04	kg
	SO_2	3.39E+04	kg
	HCl	2.49E+04	kg
	HF	7.10E+03	kg
	Cd	1.02E+02	kg
	Ni	3.12E+02	kg
	As	5.24E+02	kg
	Hg	6.14E+02	kg
	PCDF	1.18E-06	kg
	CO_2	1.95E+08	kg
	CO	1.36E+04	kg
	CH_4	1.84E+04	kg
	NH_3	5.15E+03	Kg
	H_2S	4.37E+03	kg
	NMHC	2.11E+03	kg

Impact Assessment

Environmental impact assessment was using the EDIP 2003 and CED methods. The EDIP 2003 method was chosen because of its emphasis on impact categories related to environmental issues. This method uses a single score that can quantify diverse impacts [21]. Environmental impact categories are described in Table 1.

T

he results of the characterization of the potential environmental impacts of 271,282.14 tons of waste are shown in Table 14 and Figure 7. These findings indicate that the results of each potential environmental impact generated vary, as shown by the EDIP 2003 method. Based on the CED Impact assessment method, the energy generated by each scenario is partly non-renewable. However, its value is not as significant as that generated by renewable energy.

Table 14. Characterization Value Results

Impact Classification	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
GWP100a (kg CO_2 eq)	3.62E+12	5.65E+12	1.90E+08	8.48E+11	1.57E+08
Ozone Formation Vegetation (m^2.ppm.h)	6.09E+13	9.50E+13	1.91E+08	1.43E+13	1.76E+08
Ozone Formation Human (person.ppm.h)	4.46E+09	6.96E+09	1.27E+04	1.05E+09	1.21E+04
Acidification (m^2)	1.99E+11	3.10E+11	1.23E+06	4.66E+10	1.44E+06
Terrestrial Eutrophication (m^2)	4.50E+11	7.03E+11	2.69E+06	1.05E+11	3.96E+06
Aquatic Eutrophication (N) (kg N)	4.89E+09	2.66E+09	1.02E+04	1.15E+09	1.23E+04
Human Toxicity Air (person)	1.01E+16	5.17E+13	4.07E+09	1.01E+16	1.01E+16
Human Toxicity Water (m^3)	1.34E+15	2.38E+10	5.03E+08	1.34E+15	1.34E+15
Human Toxicity Soil (m^3)	8.90E+10	3.36E+07	6.33E+05	8.90E+10	8.90E+10
Ecotoxicity Water Chronic (m^3)	4.47E+15	7.48E+10	1.32E+08	4.47E+15	4.47E+15

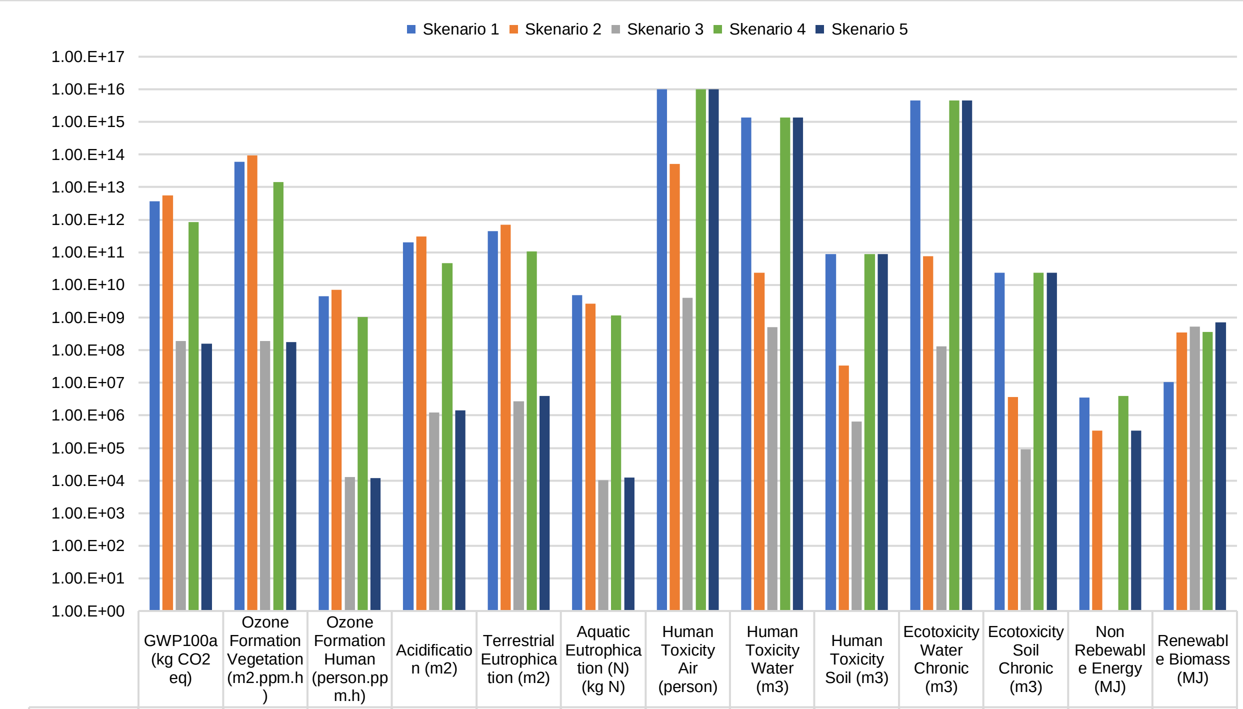
EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

Ecotoxicity Soil Chronic (m^3)	2.40E+10	3.63E+06	9.08E+04	2.40E+10	2.40E+10
Non-Renewable Energy (MJ)	3.53E+06	3.37E+05	0	3.87E+06	3.37E+05
Renewable Biomass (MJ)	1.04E+07	3.46E+08	5.31E+08	3.57E+08	7.03E+08

As described in the EDIP 2003 method, the normalization process involves converting impact characterization values using normalization factors, thus facilitating the comparison of environmental impact values. The results of the normalization are presented in Table 15.

Table 15 Normalization Value Results

Impact Classification	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
GWP100a	4.67E+08	7.29E+08	2.45E+04	1.09E+08	2.02E+04
Ozone Formation (Vegetation)	1.02E+09	1.60E+09	3.21E+03	2.40E+08	2.95E+03
Ozone Formation (Human)	1.57E+09	2.45E+09	4.48E+03	3.68E+08	4.26E+03
Acidification	5.05E+08	7.89E+08	3.11E+03	1.18E+08	3.66E+03
Terrestrial Eutrophication	3.29E+08	5.13E+08	1.96E+03	7.70E+07	2.89E+03
Aquatic Eutrophication	5.87E+08	3.19E+08	1.22E+03	1.38E+08	1.48E+03
Human Toxicity Air	2.13E+07	1.09E+05	8.59E+00	2.13E+07	2.13E+07
Human Toxicity Water	2.85E+10	5.04E+05	1.07E+04	2.85E+10	2.85E+10
Human Toxicity Soil	1.10E+07	4.17E+03	7.85E+01	1.10E+07	1.10E+07
Ecotoxicity Water Chronic	1.22E+09	2.04E+04	3.60E+01	1.22E+09	1.22E+09
Ecotoxicity Soil Chronic	3.28E+05	4.98E+01	1.24E+00	3.28E+05	3.28E+05



	GWP100a (kg CO2 eq)	Ozone Formation Vegetation (m2.ppm.h)	Ozone Formation Human (person.ppm.h)	Acidification (m2)	Terrestrial Eutrophication (m2)	Aquatic Eutrophication (N) (kg N)	Human Toxicity Air (person)	Human Toxicity Water (m3)	Human Toxicity Soil (m3)	Ecotoxicity Water Chronic (m3)	Ecotoxicity Soil Chronic (m3)	Non Rebewable Energy (MJ)	Renewable Biomass (MJ)
Skenario 1	3.62.E+12	6.09.E+13	4.46.E+09	1.99.E+11	4.50.E+11	4.89.E+09	1.01.E+16	1.34.E+15	8.90.E+10	4.47.E+15	2.40.E+10	3.53.E+06	1.04.E+07
Skenario 2	5.65.E+12	9.50.E+13	6.96.E+09	3.10.E+11	7.03.E+11	2.66.E+09	5.17.E+13	2.38.E+10	3.36.E+07	7.48.E+10	3.63.E+06	3.37.E+05	3.46.E+08
Skenario 3	1.90.E+08	1.91.E+08	1.27.E+04	1.23.E+06	2.69.E+06	1.02.E+04	4.07.E+09	5.03.E+08	6.33.E+05	1.32.E+08	9.08.E+04	0.00.E+00	5.31.E+08
Skenario 4	8.48.E+11	1.43.E+13	1.05.E+09	4.66.E+10	1.05.E+11	1.15.E+09	1.01.E+16	1.34.E+15	8.90.E+10	4.47.E+15	2.40.E+10	3.87.E+06	3.57.E+08
Skenario 5	1.57.E+08	1.76.E+08	1.21.E+04	1.44.E+06	3.96.E+06	1.23.E+04	1.01.E+16	1.34.E+15	8.90.E+10	4.47.E+15	2.40.E+10	3.37.E+05	7.03.E+08

Figure 7. Impact Characterization

The weighting process converts normalized impact values with weighting factors used in EDIP 2003 to assess various activities contributing to environmental impacts. This step is done by

CIVED Journal of Civil Engineering and Vocational Education
EISSN: 2622-6774
Vol. 12 No.1 March 2025
http://cived.ppj.unp.ac.id/index.php/CIVED

classifying each value of each impact category based on processes and activities with predetermined limits. The weighting results (single score) can be seen in Table 16 and Figure 8.

Table 16. Single Score LCA

Impact Classification	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
GWP100a	5.14E+08	8.02E+08	2.69E+04	1.20E+08	2.23E+04
Ozone Formation (Vegetation)	1.23E+09	1.92E+09	3.85E+03	2.88E+08	3.54E+03
Ozone Formation (Human)	1.89E+09	2.94E+09	5.37E+03	4.42E+08	5.11E+03
Acidification	6.57E+08	1.03E+09	4.05E+03	1.54E+08	4.76E+03
Terrestrial Eutrophication	3.94E+08	6.15E+08	2.36E+03	9.24E+07	3.47E+03
Aquatic Eutrophication	8.22E+08	4.46E+08	1.71E+03	1.93E+08	2.07E+03
Human Toxicity Air	2.34E+07	1.20E+05	9.44E+00	2.34E+07	2.34E+07
Human Toxicity Water	3.70E+10	6.55E+05	1.38E+04	3.70E+10	3.70E+10
Human Toxicity Soil	1.32E+07	5.01E+03	9.43E+01	1.32E+07	1.32E+07
Ecotoxicity Water Chronic	0	0	0	0	0
Ecotoxicity Soil Chronic	0	0	0	0	0
Total	**4.25E+10**	**7.74E+09**	**5.82E+04**	**3.83E+10**	**3.70E+10**

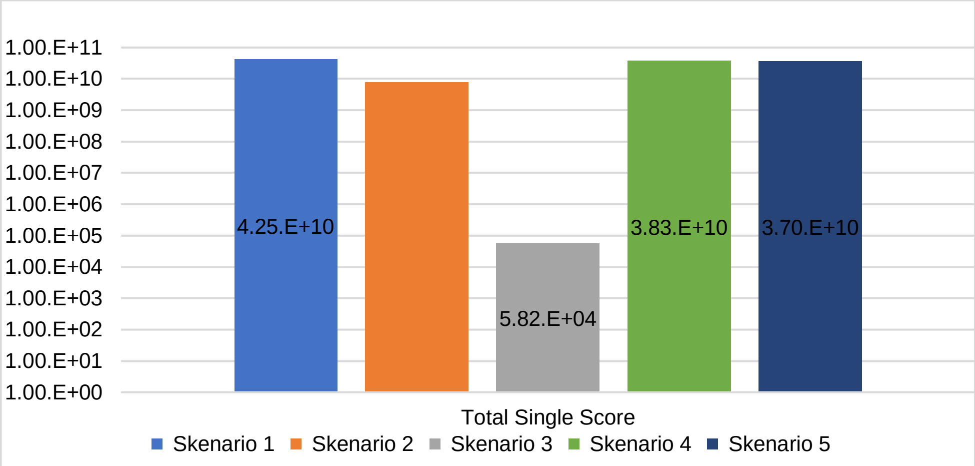


Figure 8. LCA Single Score Value

Interpretation (Comparative Analysis)

Based on the LCIA results using the CED method in **Table 14** and **Figure 7**, the most significant amount of renewable energy is produced by Scenario 5 with a total renewable energy value of 7.02E+08 MJ, followed by Scenario 3 with a value of 5.31E+08 MJ. Scenario 3 is the best scenario for the non-renewable energy category because scenario 3 does not produce non-renewable energy. The LCIA results using the EDIP 2003 method in **Table 14** and Figure 7 show that:

1. GWP100a
   The smallest GWP100a impact is in scenario 5, with a value of 1.57E+08 kg CO_2 eq, followed by scenario 3, with a value of 1.90E+08 kg CO_2 eq. The largest GWP100a impact is generated by scenario 2, with a value of 5.65E+12 kg CO_2 eq.
2. Ozone Formation (Vegetation)
   The slightest impact of Ozone Formation (Vegetation) is in scenario 5, with a value of 1.76E+08 m^2.ppm.h, followed by scenario 3, with a value of 1.91E+08 m^2.ppm.h. The most significant impact of Ozone Formation (Vegetation) is generated by scenario 2 with a value

of 9.50E+13 m^2.ppm.h.

3. Ozone Formation (Human)
   The smallest Ozone Formation (Human) impact is in scenario 5, with a value of 1.21E+04 person.ppm.h, followed by scenario 3, with a value of 1.27E+04 person.ppm.h. The largest Ozone Formation (Human) impact is in scenario 2, with a value of 6.96E+09 person.ppm.h.
4. Acidification
   The smallest Acidification impact is in scenario 3, with a value of 1.23E+06 m^2, followed by scenario 5, with a value of 1.44E+06 m^2. The largest Acidification impact is generated by scenario 2, with a value of 3.10E+11 m^2.
5. Terrestrial Eutrophication
   The smallest Terrestrial Eutrophication impact is in scenario 3, with a value of 2.69E+06 m^2, followed by scenario 5, with a value of 3.96E+06 $m^{2.}$ The largest Terrestrial Eutrophication impact is generated by scenario 2, with a value of 7.03E+11 m^2.
6. Aquatic Eutrophication
   The smallest Aquatic Eutrophication impact was in scenario 3, with a value of 1.02E+04 kg N, followed by scenario 5, with a value of 1.23E+04 kg N. The largest Aquatic Eutrophication impact was produced by scenario 1, with a value of 4.89E+09 kg N.
7. Human Toxicity Air
   The smallest Human Toxicity Air impact is in scenario 3, with a value of 4.07E+09 person, followed by scenario 2, with a value of 5.17E+13 person. The largest Human Toxicity Air impact is generated by scenarios 1, 4, and 5 with a value of 1.01E+16 person.
8. Human Toxicity Water
   The most minor Human Toxicity Water impact is in scenario 3, with a value of 5.03E+08 m^3, followed by scenario 2, with a value of 2.38E+10 $m^{3.}$ Scenarios 1, 4, and 5 generate the most considerable Human Toxicity Water impact with a value of 1.34E+15 m^3.
9. Human Toxicity Soil
   The smallest impact of Human Toxicity Soil is in scenario 3 with a value of 6.33E+05 m^3, followed by scenario 2 with a value of 3.36E+07 m^3. The largest impact of Human Toxicity Soil is produced by scenarios 1,4 and 5 with a value of 8.90E+10 m^3.
10. Exotoxicity Water Cronic
    The smallest impact of Ecotoxicity Water Chronic is in scenario 3, with a value of 1.32E+08 m^3, followed by scenario 2, with a value of 7.48E+10 m^3. The largest impact of Ecotoxicity Water Chronic is produced by scenarios 1,4 and 5 with a value of 4.47E+15 m^3.
11. Ecotoxicity Soil Cronic
    The smallest impact of Soil Chronic Ecotoxicity is in scenario 3, with a value of 9.08E+04 m^3, followed by scenario 2, with a value of 3.63E+06 m^3. The largest impact of Soil Chronic Exotoxicity is produced by scenarios 1,4 and 5 with a value of 2.40E+10 m^3.

The Single Score results on each impact in Table 16 and Figure 8 show that environmentally friendly technology is in scenario 3, namely gasification technology.

WtE Technology Selection Analysis

The selection of the most appropriate technology depends on several factors, including waste processing capacity, available land area, energy production potential, and a single LCA score. Each factor will be assigned a weighted score ranging from 1 to 5, with the technology achieving the highest total identified as the optimal choice. This assessment is designed to facilitate the identification of the most appropriate and efficient technology for Padang City. The findings of this assessment are presented in Table 17.

Table 17 Results of WtE Technology Selection Assessment

Assessment Aspect	RDF	AD	Gasification	RDF+AD	Gasification+AD
Amount of Processed Solid Waste (ton/day)	710	431	743	710	743
Value	**3**	**1**	**3**	**3**	**3**
Energy Produced (GWh/ tahun)	37	96	150	122	158
Value	**1**	**2**	**3**	**3**	**4**
Land Area Required (m^2)	48,800	37,746	5,101	57,266	39,786
Value	**1**	**2**	**5**	**1**	**2**
Single Score LCA	4,25E+10	7,74E+09	5,82E+04	3,83E+10	3,70E+10
Value	**1**	**4**	**5**	**1**	**1**
Total	**6**	**9**	**16**	**8**	**10**

CONCLUSION

Solid waste generation in Padang City is estimated to reach 338,927 tons annually, with 2031 as the projection reference point. The proposed solution to this problem is to apply waste-to-energy (WtE) technology, including RDF, AD, and gasification processes. The land area required for each technology is 48,800 m^2 for RDF processing, 37,736 m^2 for AD processing, and 5,101 m^2 for Gasification processing. The amount of solid waste that can be processed in 2031 from RDF, AD, and Gasification technologies is 710 tons/day, 431 tons/day, and 743 tons/day, respectively. The assumption is that the solid waste entering the landfill is 80% of the total solid waste. The single score LCA results show that each WtE technology's environmental impact is 4.25E+10 Pt for RDF, 7.74E+09 Pt for AD, and 5.82E+04 Pt for Gasification. Based on the assessment results, the appropriate WtE technology to use is gasification. This selection is because the highest value obtained is 16. Gasification shows that more solid waste can be processed, the energy produced is higher, the land requirement is minor, and the single score LCA results are low compared to other WtE technologies.

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