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Energy Potential Generated from Municipal Solid Waste (MSW) at Tamangapa Landfill in Makassar City

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Abstract: This study aims to analyse the potential energy that can be generated from municipal solid waste (MSW) at Tamangapa landfill, check the adequacy of energy according to the target of 20 MW/day, and give consideration to WtE technologies that can be applied. The research began with a literature study, followed by a quantitative approach to calculate the potential energy that can be generated through incineration, gasification, pyrolysis, anaerobic digestion (AD) and fermentation WtE technologies. The results showed that the energy target of 20 MW/day from MSW in Makassar can be met through incineration (168.80 MW/day), gasification (28.29 MW/day) and pyrolysis (62.03 MW/day). However, if 20 MW/day is clean energy, then considering the energy conversion efficiency, 30.38 MW/day is obtained for incineration, 7.07 MW/day for gasification, and 15.51 MW/day for pyrolysis. Based on this calculation, only incineration technology can fulfil the 20 MW/day energy target as expected. In order to maximise the energy potential, it is recommended to use a combination of incineration WTE technologies for plastic, rubber, paper and fabric components, and pyrolysis for wood and food waste components.

Keywords: Gasification; Inceneration; LHV; MSW; Tamangapa landfill

Introduction

Based on data from the Ministry of Environment and Forestry, it's thought that the 301 regencies/cities in Indonesia generate around 35.42 million tons of waste a year (SIPSN, 2021), but only about 37.94% of it is properly managed. This means that we need to manage this waste effectively and work together with other parties because if it builds up, it can cause all kinds of disasters, including environmental damage, floods, landslides, fires and diseases (Afla et al., 2023; Prarikeslan et al., 2023). Every year, the amount of waste in the city of Makassar is increasing. The Makassar Environmental Department has the figures, which show that the average annual increase in waste is 11.53%, in line with a population growth rate of 1.30% per year (Chandra, 2023). The latest figures from the Makassar Environmental Department show that the city is producing 7,374.5 tons of waste a month, or 245.8 tons a day. The majority of this is organic food waste, which accounts for 38.82% (Andini, 2023; Rahma et al., 2023).

Generally, this waste is disposed of in open landfills, undergoing both biological and chemical reactions that generate methane gas (Hesnawi et al., 2013; Khairunnisa et al., 2023) and release heat. This heat can lead to spontaneous combustion, considered a major cause of environmental pollution and a significant health threat to communities residing near waste disposal sites (Chavan et al., 2022). Methane gas explosions often occur, as seen in the explosion at the Cireundeu landfill in Leuwigajah, Kota Cimahi, West Java, on January 21, 2005 (Setiawan, 2021). In Makassar, there have been several instances of fires at the

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Tamangapa landfill in September and October 2019 and August 2021 (Yunus, 2012).

A new paradigm regarding waste has emerged, changing the way we perceive it. Waste, traditionally considered something dirty, disease-ridden, and hazardous, necessitating disposal and destruction, is now viewed as something that can provide benefits to both life and the environment when managed properly. One form of sustainable waste treatment involves transforming waste to energy (WtE) (Fatimah et al., 2023). This aligns with the program initiated by the Indonesian Government to reduce dependence on diminishing fossil energy reserves such as oil and coal. This directive is mandated through Government Regulation No. 79 of 2014 concerning the National Energy Policy of the Indonesian Government, targeting a 23% utilization of new and renewable energy (EBT) non-fossil sources. This is expected to decrease fossil energy consumption from 48% to 25% (DEN, 2014). Additionally, Ministerial Decision No. 2682 K/21/MEM/2008 supports the availability of environmentally safe electricity to meet energy needs.

The Ministry of Energy and Mineral Resources has released data indicating that Municipal Solid Waste (MSW) nationwide has the potential to generate environmentally friendly electrical energy of 49,810 MW. However, only 445 MW, or 0.89% of the total potential, is currently utilized. Specifically for biogas from waste, out of 38 cities and regencies in Indonesia, the estimated electrical potential is around 236 MW (Hermawan, 2017).

As of now in Indonesia, the utilization of urban waste collected at landfills for conversion into energy is not fully optimized. This is evident from the fact that out of the 12 planned Waste-to-Energy Power Plants, only two have been realized: Waste-to-Energy Power Plant Benowo in Surakarta and Waste-to-Energy Power Plant Putri Cempo in Surabaya. Makassar is among the 12 cities planned for the construction of a Waste-to-Energy Power Plant with a capacity of 20 MW per day, utilizing MSW from the Tamangapa Landfill. The location of the planned Waste-to-Energy Power Plant is in the Makassar Industrial Area, Tamalanrea sub-district, Makassar City.

The Tamangapa Landfill serves as the primary final waste processing facility for the residents of Makassar, totaling 1,436,626 people as of 2023 (BPS Sul-Sel, 2023). Located approximately 15 km from the city center of Makassar, the Tamangapa Landfill spans an area of 23.74 hectares and is situated in the Tamangapa sub-district, Manggala district, Makassar city, South Sulawesi province, Indonesia (Rusman et al., 2023). The waste processing system at the Tamangapa Landfill still employs an open dumping system. According to data from the Makassar Environmental Department, the average amount of Municipal Solid Waste (MSW) entering the Tamangapa Landfill from 2020 to 2022 is around 738.23 tons per day or 269,453.13 tons per year. The increasing daily waste intake, coupled with the lack of adequate initial waste processing, may reduce the landfill capacity, leading to a potential overload in the future. The composition of MSW entering the Tamangapa Landfill is predominantly plastic waste at 38.56%, followed by food waste at 26.92%, miscellaneous items at 18.20%, and the remaining approximately 17% consisting of rubber, wood, paper, fabric, glass, and metal. The amount and composition of waste generated over three years (2020, 2021, 2022) are presented in Table 1.

Table 1. Total Waste Generation at Tamangapa Landfill

Waste components	Comp. (%)	Total waste component generation (tons/year) 2020	2021	2022
Plastic	38.56	98,545.87	107,151.33	106,006.18
Rubber	1.07	2,734.55	2,973.34	2,941.56
Wood	8.19	20,930.78	22,758.54	22,515.32
Paper	0.01	25.56	27.79	27.49
Fabric	5.04	12,880.48	14,005.26	13,855.58
Food waste	26.92	68,798.10	74,805.85	74,006.39
Glass	1.72	4,395.72	4,779.57	4,728.49
Metal	0.29	741.14	805.86	797.25
Others	18.20	46,512.83	50,574.54	50,034.04
Total	100	255,565.02	277,882.07	274,912.29

In light of the challenges encountered at the Tamangapa Landfill and in alignment with the government's objective to construct a Waste-to-Energy (WtE) Power Plant, a research initiative was undertaken with the objective of quantifying the potential energy output that could be generated from Municipal Solid Waste (MSW) at the Tamangapa Landfill through the utilisation of WtE technologies. These technologies can be broadly categorised into two principal processes: thermochemical processes, which encompass incineration, gasification, and pyrolysis; and biochemical processes, which include anaerobic digestion (AD) and fermentation. The anticipated outcomes of this study include the provision of data regarding the potential energy generation, the suitability of the planned capacity of 20 MW, and the selection of appropriate WtE technologies for implementation.

Method

The calculation of energy potential is based on the data of waste components and compositions entering the Tamangapa Landfill in 2020, 2021, and 2022 (Table 1), assuming a constant waste composition each year. The potential energy generated from inseneration is calculated using the first equation, while for gasification, pyrolysis, AD, and fermentation it is calculated using the second equation. The equations are formulated as follows:

$$E = 1.162*10^{-6}*(LHV)_c*W \quad (1)$$
$$E = 2.778*10^{-7}*(LHV)_f*S \quad (2)$$

Where: E = energy potential generated (MWh/year), $(LHV)_c$ = low heat value of each waste component (kcal/kg), W = quantity of waste components (kg/year), $(LHV)_f$ = low heat value of the produced products such as syngas, bio-oil, biochar, or biofuel (kJ/kg), and S = quantity of yield products (kg/year). $(LHV)_c$ and $(LHV)_f$ are determined based on research conducted by (Novita et al. (2010), Mujiarto et al. (2021), Gandidi et al. (2018), Islam et al. (1970), Cedigaz (2019), and Qanaze et al. (2021). The calculated energy potential is a gross value before application to engines or equipment. The research flow can be seen in Figure 1.

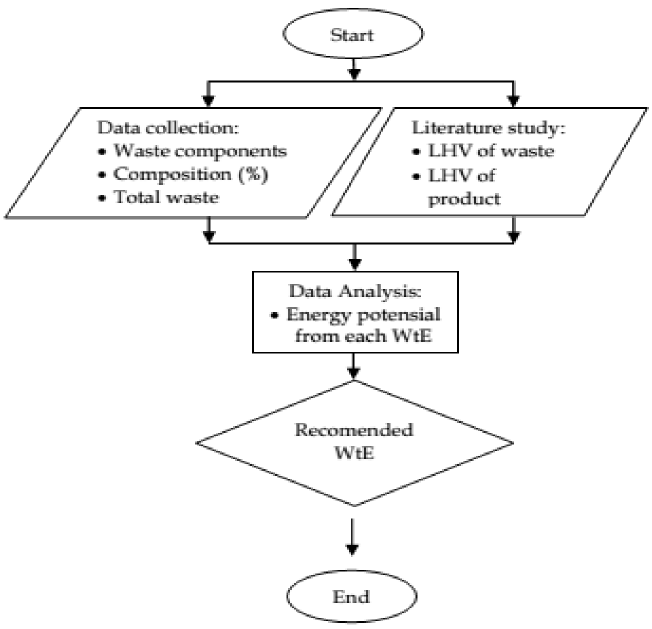

Figure 1. Research flow

After obtaining the average potential energy that can be generated from each process technology in MW/year or MW/day, the results were compared with the 20 MW/day electrical energy target as expected. The next step is to provide recommendations to the Makassar city government regarding the appropriate WtE technology to be applied in processing Makassar city solid waste into energy.

Result and Discussion

Incineration

Incineration is one of the thermal technologies for MSW processing, where MSW is treated in the form of Refuse-Derived Fuel (RDF) or directly burned at temperatures ranging from 700 to 1400 °C in sufficient air conditions (Jain et al., 2014; Knox, 2005; Kumar et al., 2017; Qazi et al., 2018; Ramadhan et al., 2021). This technology can process all types of organic and inorganic waste (except metals and glass), reducing MSW volume by up to 80-90% (Akinshilo, 2019; Arias et al., 2018; Chakraborty et al., 2013; Ramadhan et al., 2021). Another advantage of incineration is its ability to reduce water and gas pollution produced from waste accumulation (Kothari et al., 2010).

Incineration transforms waste into hot combustion gases, ash, and particulates (Knox, 2005). The combustion heat can be utilized in a steam power plant to heat water in a boiler, turning it into steam. The generated steam then rotates a steam turbine connected to a generator. The electrical energy produced ranges from 500-600 kWh for every ton of waste (Pavlas et al., 2011).

The amount of energy that can be generated from MSW at the Tamangapa Landfill through incineration is calculated using Equation (1), and the results can be seen in Table 2. The Low Heat Value (LHV) of each waste component is based on the research conducted by Novita et al. (2010) on waste characteristics in Indonesia.

Table 2. Energy Potential Generated Through Incineration

Waste components	LHV (kcal/kg)	Energy potential generated (MWh/year) 2020	2021	2022
Plastic	10,382.32	1,189,087.24	1,292,923.51	1,279,105.78
Rubber	5,106.45	16,228.75	17,645.92	17,457.33
Wood	906.08	22,041.07	23,965.80	23,709.67
Paper	2,884.84	85.68	93.17	92.17
Fabric	4,010.65	60,038.19	65,280.98	64,583.31
Sampah makanan	1,437.86	114,967.20	125,006.63	123,670.66
Total		1,402,448.13	1,524,916.01	1,508,618.93

Gasification

Gasification is one of the thermochemical biomass conversion processes where raw materials undergo oxidation under limited oxygen conditions, resulting in incomplete combustion (Knoef, 2012). Gasification temperatures range from 600-1200°C (Adams et al., 2018) or 800-1600°C (Kumar et al., 2017). The gasification products include synthesis gas (syngas), H_2, and CO formed at temperatures above 1200°C, while at lower temperatures, gases like CO, H_2, CH_4, and CO_2 are produced (Adams et al., 2018). Other products include solids such as ash, slag, heavy metals, and others (Knoef, 2005). The produced gas can be used for combustion heat in boilers, electricity through a Combined Heat and Power (CHP) system, or converted into liquid fuel (Adams et al., 2018).

Table 3. Energy Potential Generated Through Gasification

Waste components	Energy potential generated (MWh/year) 2020	2021	2022
Plastic	113,246.54	124,207.24	121,819.74
Rubber	3,142.47	3,446.62	3,380.37
Wood	24,053.14	26,381.15	25,874.06
Paper	29.37	32.21	31.59
Fabric	14,801.93	16,234.56	15,922.50
Food waste	79,061.12	86,713.15	85,046.36
Total	234,334.57	257,014.93	252,074.62

Generally, gas produced from gasification has a LHV of 4–10 MJ/Nm^3, lower than natural gas with a Lower Calorific Value (LCV) of around 38 MJ/Nm^3 (Seo et al., 2018). Studies by Alauddin et al. (2010) and Zhou et al. (2009) indicate that syngas obtained ranges from 1-2.6 m^{3}gas/kg of biomass. Through steam gasification, hydrogen with high concentration and nitrogen-free syngas with an LHV ranging from 15 to 20 MJ/m^3 can be produced (Knoef, 2005). Approximately 500–2500 m^3/ton of syngas can be produced by applying this process (Ahmad et al., 2016). Gu et al. (2020) found in their research, using MSW with specific composition, that optimal gasification occurred at a temperature of 650°C with 1.25% oxygen concentration, resulting in 0.296 L/g of syngas with an LHV of 10.98 kJ/L. Another study conducted by Mujiarto et al. (2021) on MSW (60% organic and 40% inorganic) with multi-stage downdraft gasification yielded syngas with a composition of 19.08% CO, 10.89% H_2, 1.54% CH_4, and an LHV of 4,137 kJ/kg, with a tar content of 57.29 mg/Nm^3. In this study, the calculation of the potential energy generated is based on the research conducted by Mujiarto et al. (2021) because it is more suitable for the characteristics of MSW in Indonesia, especially since the LHV of syngas obtained is higher than that reported by Gu et al. (2020). Based on various literature, the energy that can be generated through gasification according to the composition and quantity of waste entering the Tamangapa Landfill is presented in Table 3.

Pyrolysis

Pyrolysis is a process where waste materials can be thermally degraded without oxygen to produce products such as bio-oil, syngas, and biochar (Sun et al., 2021). The process temperature ranges from 300°C to 900°C (Cheng, 2017). The quantity and quality of pyrolysis products obtained depend on the processing temperature, heating rate, residence time of the raw material, as well as the composition and particle size of the waste (Kalyani et al., 2014; Lombardi et al., 2015). Pyrolysis is considered the best alternative, as it is an easy and clean technology for MSW processing compared to other WtE technologies (Cheng, 2017).

According to Hasan et al. (2021), MSW pyrolysis can yield approximately 43% bio-oil, 25% syngas, and 27% biochar. Gandidi et al. (2018), using a sample of MSW (plastic, biomass, paper, rubber, and fabric) weighing 500 g, with the process type: slow pyrolysis; reactor type: vacuum fix bed; catalyst: natural zeolite, obtained: 28.6% biochar, 21.4% bio-oil, and 50% syngas. Research with atmospheric pressure fast pyrolysis, particle size <3 mm, residence time 0.5 – 2 s, temperature 400 - 550°C can produce 65-75% bio-oil, 13-25% syngas, and 12-19 biochar (Czernik et al., 2004; Iribarren et al., 2012; Isahak et al., 2012). Pyrolysis conducted on previously sun-dried MSW showed that the maximum bio-oil yield was obtained at a temperature of 500°C, for 35 minutes, at a pressure of 0.001 mmHg. The Lower Heating Value (LHV) of bio-oil obtained was 12.01 MJ/kg (Islam et al., 1970). Another study by Qanaze et al. (2021) on MSW using slow pyrolysis method obtained Biochar with an LHV of 15.6 MJ/kg.

The estimated energy potential that can be generated from the Tamangapa Landfill through the pyrolysis process can be seen in Table 4. The calculation is based on the percentage of bio-oil, syngas, and biochar obtained from the study by Gandidi *et al.* (2016), while the LHV values for bio-oil are taken as 12 MJ/kg (Islam et al., 1970), LHV for syngas as 4,137 kJ/kg (Mujiarto et al., 2021), and LHV for biochar as 15.6 MJ/kg (Qanaze et al., 2021).

Table 4. Energy Potential Generated From Pyrolysis

Waste components	Energy potential generated (MWh/year)								
			2020			2021			2022
	Bio-Oil	Syngas	Biochar	Bio-Oil	Syngas	Biochar	Bio-Oil	Syngas	Biochar
Plastic	70,296.62	56,623.27	122,132.16	76,435.22	61,567.86	132,797.27	75,618.35	60,909.87	131,378.04
Rubber	1,950.66	1,571.24	3,389.04	2,121.00	1,708.44	3,684.99	2,098.33	1,690.19	3,645.60
Wood	14,930.74	12,026.57	25,940.41	16,234.56	13,076.78	28,205.64	16,061.05	12,937.03	27,904.21
Paper	18.23	14.68	31.67	19.82	15.97	34.44	19.61	15.80	34.07
Fabric	9,188.15	7,400.97	15,963.33	9,990.50	8,047.25	17,357.32	9,883.73	7,961.25	17,171.82
Food waste	49,076.37	39,530.56	85,264.46	53,361.94	42,982.54	92,710.13	52,791.65	42,523.18	91,719.32
Sub Total	145,460.77	117,167.29	252,721.09	158,163.03	127,398.84	274,789.79	156,472.71	126,037.31	271,853.06
Total			515,349.14			560,351.67			554,363.08

Anaerob Digestion

Anaerobic Digestion is a biochemical process that utilizes complex metabolic reactions where microorganisms break down biodegradable materials, such as food waste, animal manure, and agricultural waste, without the presence of oxygen, to produce biogas (Deublein et al., 2008; Hall et al., 2012; Wang, 2013). This conversion process is similar to composting, but composting is aerobic (involves oxygen) in the breakdown of organic matter. Technological advancements in AD have facilitated the treatment of various food wastes, making it a suitable solution for producing renewable energy, reducing greenhouse gas emissions (Gebauer, 2004; Khan, 2020; Nasir et al., 2012; Wang, 2013), and easing the waste management burden in landfills (Kosseva, 2011; Melville et al., 2014; Pham et al., 2015).

The primary products of AD are biogas and digestate. Biogas is a mixture of 50%–60% methane, 40%–50% carbon dioxide, and small amounts of other trace gases such as H_2 (1-5%), N_2 (0.5%), CO, H_2S, and water vapor (Dar et al., 2019; Deublein et al., 2008). Meanwhile, digestate is a nutrient-rich material that can be used as organic fertilizer (Kabeyi et al., 2022). The generated biogas contains about 20%–40% of the Lower Heating Value (LHV) of the raw material (McKendry, 2002). The calorific value of biogas is significantly determined by the methane composition it contains, varying from 45% to 75% volume (Cedigaz, 2019). Based on this methane composition, the LHV of biogas also varies from 16 MJ/m^3 to 28 MJ/m^3 (Cedigaz, 2019).

According to Achinas et al. (2017), Stuckl et al. (2012), Kabeyi et al. (2022), biogas generated from MSW ranges around 101.5 m^3/ton of waste. Assuming an LHV of biogas as 28 MJ/m^3, this would result in an energy yield of 2,842 MJ or 0.789 MWh/ton of waste.

In this study, the calculation of the potential energy generated is done only for wood and food waste components, with an energy yield of 0.789 MWh per ton of waste, and the results can be seen in Table 5.

Table 5. Energy Potential Generated from AD

Waste components	Energy potential generated (MWh/year) 2020	2021	2022
Wood	16,523.70	17,966.62	17,774.61
Food waste	54,312.32	59,055.11	58,423.98
Total	70,836.02	77,021.73	76,198.58

Fermentation

Fermentation is an anaerobic biological process in which simple sugars from biomass raw materials are converted into alcohol and carbon dioxide through the action of various microorganisms, which is then distilled to produce ethanol in liquid form (Adams et al., 2018). Several studies have been conducted to develop strategies related to the utilization of solid waste for biofuel production. Gas fermentation, recently emerging as a new concept, has proven to be the best alternative in addressing various issues related to waste management (Khushboo et al., 2020; Muliarta et al., 2023; Septianingrum et al., 2023).

Table 6. Bioethanol Production From Food Waste Based on Several Studies (Bibra et al., 2022)

Substrate and amount of substrate (g/L)	Pretreatment	Organism	Fermentation conditions	Fermentation type	Bioprocess type	Yield (g ethanol/g food waste)	Reference
200	None	Geobacillus thermoglucosidasius dan Thermoanaerobacter ethanolicus	T = 60 ◦C pH = 6.5 Agitation speed = 100 rpm Inoculum = 5% (v/v)	Fed-Batch, submerged with media components and inoculum addition at intervals	Consolidated bioprocessing	0.1	(Bibra et al., 2020)
330	Screw pressed and dried using steam boiler at 150 ◦C Dilute acid treatment (H2SO4 0.4% w/v at 160 ◦C for 64.5 min)	Issatchenkia orientalis	T = 30 ◦C pH = 3.0 Agitation speed = 200 rpm Inoculum = 5% (v/v	Batch, submerged	Separate Hydrolysis and Fermentation	0.04	(Kim et al., 2018)
2000	Enzymatic pretreatment (amylase 10 U		T = 30 ◦C pH = 5.0 Agitation speed = 100 rpm Inoculum = 2% (v/v)	Batch, Submerged	Separate Saccharification and Fermentation	0.045	(Yan et al., 2012)

Substrate and amount of substrate (g/L)	Pretreatment	Organism	Fermentation conditions	Fermentation type	Bioprocess type	Yield (g ethanol/g food waste)	Reference
	and 120 U glucoamylase/ g fed food waste for at 55 ◦C for 4 h)	Saccharomyces cerevisiae sp, H058 (wild)					

Various types of food waste can be processed through fermentation methods. For every 1 kg of the organic fraction of food waste, which consists of starch (586.3 g), cellulose (56.3 g), lipids (64.5 g), and protein (83 g), theoretically, it can be converted into 364 g of ethanol or 383.2 L of methane (Bibra et al., 2020; Mahmoodi et al., 2018). Food waste from restaurants, cafeterias, fruit and vegetable processing units, and carbohydrate-rich grains can be utilized as substrates for bioethanol production (Wang, 2013). The production of ethanol fuel from organic waste and food generates 0.86 liters of 95% ethanol from 2500g of waste paper and corn substrates, each converted into 42% to 63% fermentable sugars (Akpan et al., 2008). Ethanol produced through fermentation has proven to be widely used as a transportation fuel for cars, trucks, and trains (Carey, 2022). Other researchers who have conducted studies on bioethanol production from food waste through the fermentation process are presented in Table 6.

The largest ethanol production reported among the three studies mentioned above is 0.1 g ethanol/g of food waste (Bibra et al., 2020). Assuming the LHV of ethanol is 27 MJ/kg (Heywood, 1998), the potential energy that can be generated from each kilogram of food waste through fermentation is 2.7 MJ or 0.750 MWh. The energy potential that can be generated from food waste at the Tamangapa Landfill is shown in Table 7.

Table 7. Energy Potential Generated Through Fermentation

Waste components	Energy potential generated (MWh/year) 2020	2021	2022
Food waste	51,598.99	56,104.84	55,505.24

Based on the calculation results, it is evident that the highest average energy potential that can be generated from the thermochemical processes with the same MSW components is obtained from the incineration process, amounting to 1,478,661.02 MWh per year. Following that, pyrolysis and gasification processes yield 247,808.04 MWh each per year (Table 8).

Table 8. Average Energy Potential Generated from Each WtE Technology

WtE technology	Processed components	Average energy potential generated (MWh/year)	(MW/day)
Incineration	plastic, rubber, wood, paper, fabric, food waste	1,478,661.02	168.80
Gasificasion	plastic, rubber, wood, paper, fabric, food waste	247,808.04	28.29
Pyrolisis	plastic, rubber, wood, paper, fabric, food waste	543,354.63	62.03
AD	wood, food waste	74,685.45	8.53
Fermentation	food waste	54,403.02	6.21

Table 9. Average Energy Potential Generated for Wood and Food Waste

WtE technology	Average energy potential generated (MWh/year) wood	food waste
Incineration	23,238.85	121,214.83
Gasificasion	25,436.12	83,606.87
Pyrolisis	55,772.33	183,320.05
AD	17,421.64	57,263.81
Fermentation	---	55,505.24

For wood, the highest energy potential is obtained from the pyrolysis process at 55,772.33 MWh/year, followed by gasification at 25,436.12 MWh/year, incineration at 23,238.85 MWh/year, and AD at 17,421.64 MWh/year. Meanwhile, for food waste, the highest energy potential is derived from the pyrolysis process at 183,320.05 MWh/year, followed by incineration at 121,214.83 MWh/year, gasification at 83,606.87 MWh/year, AD at 57,263.81 MWh/year, and fermentation at 55,505.24 MWh/year (Table 9).

Conclusion

The research results indicate that the target energy of 20 MW/day can be achieved through the incineration process (168.80 MW/day), gasification (28.29 MW/day), and pyrolysis (62.03 MW/day). However, if the 20 MW/day target refers to net energy product, the calculation must account for the energy conversion efficiency of approximately 18% for incineration and 25% for gasification and pyrolysis. This results in 30.38

MW for incineration, 7.07 MW for gasification, and 15.51 MW for pyrolysis. Based on these calculations, only the incineration technology can meet the expected 20 MW/day target. To achieve maximum energy potential, it is recommended to use a combination of WtE technologies: incineration for plastic, rubber, paper, and fabric components, and pyrolysis for wood and food waste components.

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Conflicts of Interest
The authors declare no conflict of interest.

References

Achinas, S., Achinas, V., & Euverink, G. J. W. (2017). A Technological Overview of Biogas Production from Biowaste. *Engineering*, *3*(3), 299–307. https://doi.org/10.1016/J.ENG.2017.03.002

Adams, P., Bridgwater, T., Lea-Langton, A., Ross, A., & Watson, I. (2018). Biomass Conversion Technologies. In P. Thornley & P. Adams (Eds.), *Greenhouse Gases Balances of Bioenergy Systems* (pp. 107–139). Elsevier. https://doi.org/10.1016/B978-0-08-101036-5.00008-2

Afla, R. A., Martono, D. N., & Wahyono, S. (2023). Behaviour of Food Waste Home-Composting. *Jurnal Penelitian Pendidikan IPA*, *9*(9), 6848–6853. https://doi.org/10.29303/jppipa.v9i9.4294

Ahmad, A. A., Zawawi, N. A., Kasim, F. H., Inayat, A., & Khasri, A. (2016). Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. *Renewable and Sustainable Energy Reviews*, *53*, 1333–1347. https://doi.org/10.1016/j.rser.2015.09.030

Akinshilo, A. (2019). Energy Potential From Municipal Solid Waste (MSW) for a Developing Metropolis. *Journal of Thermal Engineering*, *5*(6), 196–204. https://doi.org/10.18186/thermal.654322

Akpan, U. G., Alhakim, A. A., & Ijah, U. J. J. (2008). Production of ethanol fuel from organic and food wastes. *Leonardo Electronic Journal of Practices and Technologies*, *7*(13), 001–011. Retrieved from http://lejpt.academicdirect.org/A13/001_011.htm

Alauddin, Z. A. B. Z., Lahijani, P., Mohammadi, M., & Mohamed, A. R. (2010). Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. *Renewable and Sustainable Energy Reviews*, *14*(9), 2852–2862. https://doi.org/10.1016/j.rser.2010.07.026

Andini. (2023). Makassar Kota Dunia, faktanya volume sampah capai 7.374,5 ton perbulan. In *KabarMakassar.com*. Retrieved from https://www.kabarmakassar.com/posts/view/23716/makassar-kota-dunia-faktanya-volume-sampah-capai-7-374-5-ton-perbulan.html#

Arias, S. A., Restrepo-Cuestas, B., & Jaramillo-Duque, Á. (2018). Electricity generation potential from solid waste in three Colombian municipalities. *TecnoLógicas*, *21*(42), 111–128. https://doi.org/10.22430/22565337.782

Bibra, M., Rathinam, N. K., Johnson, G. R., & Sani, R. K. (2020). Single pot biovalorization of food waste to ethanol by Geobacillus and Thermoanaerobacter spp. *Renewable Energy*, *155*, 1032–1041. https://doi.org/10.1016/j.renene.2020.02.093

Bibra, M., Samanta, D., Sharma, N. K., Singh, G., Johnson, G. R., & Sani, R. K. (2022). Food Waste to Bioethanol: Opportunities and Challenges. *Fermentation*, *9*(1), 8. https://doi.org/10.3390/fermentation9010008

Carey, F. A. (2022). Organic Chemistry Organic Chemistry. In *Organic Chemistry Frontiers* (6th ed., Vol. 1261, Issue 6). Prentice Hall of India Private limited. http://dx.doi.org/10.1039/d1qo00478f

Chakraborty, M., Sharma, C., Pandey, J., & Gupta, P. K. (2013). Assessment of energy generation potentials of MSW in Delhi under different technological options. *Energy Conversion and Management*, *75*, 249–255. https://doi.org/10.1016/j.enconman.2013.06.027

Chandra, W. (2023). *Makassar dan Masalah Darurat Sampah*. Retrieved from https://www.mongabay.co.id/2023/03/13/makassar-dan-masalah-darurat-sampah.

Chavan, D., Arya, S., & Kumar, S. (2022). Open dumping of organic waste: Associated fire, environmental pollution and health hazards. In *Advanced Organic Waste Management* (pp. 15–31). Elsevier. https://doi.org/10.1016/B978-0-323-85792-5.00014-9

Cheng, J. (2017). *Biomass to Renewable Energy Processes, Second Edition*. CRC Press. https://doi.org/10.1201/9781315152868

Czernik, S., & Bridgwater, A. V. (2004). Overview of Applications of Biomass Fast Pyrolysis Oil. *Energy & Fuels*, *18*(2), 590–598. https://doi.org/10.1021/ef034067u

Dar, R. A., Yaqoob, M., Parmar, M., & Phutela, U. G. (2019). Biofuels from Food Processing Wastes. In *Materials Research Foundations* (Vol. 46, pp. 249–288). https://doi.org/10.21741/9781644900116-10

DEN. (2014). *Ketahanan Energi Indonesia Tahun 2014*. Jakarta: Dewan Energi Nasional.

Deublein, D., & Steinhauser, A. (2008). *Biogas from Waste and Renewable Resources*. WILEY-VCH Verlag GmbH & Co.

Fatimah, S., Marwoto, P., & Nugroho, S. E. (2023). The Electrical Characteristics of Fruit Peel Waste as a Biobattery in Terms of Fermentation Time and Coconut (Cocos nucifera L.) Pulp Concentration. *Jurnal Penelitian Pendidikan IPA*, *9*(SpecialIssue), 1008–1016. https://doi.org/10.29303/jppipa.v9iSpecialIssue.6477

Gandidi, I. M., Susila, M. D., Mustofa, A., & Pambudi, N. A. (2018). Thermal – Catalytic cracking of real MSW into Bio-Crude Oil. *Journal of the Energy Institute*, *91*(2), 304–310. https://doi.org/10.1016/j.joei.2016.11.005

Gebauer, R. (2004). Mesophilic anaerobic treatment of sludge from saline fish farm effluents with biogas production. *Bioresource Technology*, *93*(2), 155–167. https://doi.org/10.1016/j.biortech.2003.10.024

Gu, Q., Wu, W., Jin, B., & Zhou, Z. (2020). Analyses for Synthesis Gas from Municipal Solid Waste Gasification under Medium Temperatures. *Processes*, *8*(1), 84. https://doi.org/10.3390/pr8010084

Hall, G. M., & Howe, J. (2012). Energy from waste and the food processing industry. *Process Safety and Environmental Protection*, *90*(3), 203–212. https://doi.org/10.1016/j.psep.2011.09.005

Hasan, M. M., Rasul, M. G., Khan, M. M. K., Ashwath, N., & Jahirul, M. I. (2021). Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments. *Renewable and Sustainable Energy Reviews*, *145*(March), 111073. https://doi.org/10.1016/j.rser.2021.111073

Hermawan, F. (2017). *Penerapan Teknologi Waste to Energy (WTE) Pada Rencana Pembangunan Intermediate Treatment Facility (ITF) Sunter Jakarta Utara (Dalam Kaitannya Terhadap Penanganan Permasalahan Sampah di Provinsi DKI Jakarta Menuju Pembangunan yang Berkelanjutan)*. Retrieved from https://upstdlh.id/article/post-8.

Hesnawi, R. M., & Mohamed, R. A. (2013). Effect of Organic Waste Source on Methane Production during Thermophilic Digestion Process. *International Journal of Environmental Science and Development*, *4*(4), 435–437. https://doi.org/10.7763/IJESD.2013.V4.388

Heywood, J. (1998). *Internal Combustion Engine Fundamentals*. New York: McGraw-Hill Education.

Iribarren, D., Peters, J. F., & Dufour, J. (2012). Life cycle assessment of transportation fuels from biomass pyrolysis. *Fuel*, *97*, 812–821. https://doi.org/10.1016/j.fuel.2012.02.053

Isahak, W. N. R. W., Hisham, M. W. M., Yarmo, M. A., & Yun Hin, T. (2012). A review on bio-oil production from biomass by using pyrolysis method. *Renewable and Sustainable Energy Reviews*, *16*(8), 5910–5923. https://doi.org/10.1016/j.rser.2012.05.039

Islam, M. S., Miah, M. Y., Ismail, M., Jamal, M. S., Banik, S. K., & Saha, M. (1970). Production of Bio-Oil from Municipal Solid Waste by Pyrolysis. *Bangladesh Journal of Scientific and Industrial Research*, *45*(2), 91–94. https://doi.org/10.3329/bjsir.v45i2.5703

Jain, P., Handa, K., & Paul, A. (2014). Studies on Waste-to-Energy Technologies in India & a detailed study of Waste-to-Energy Plants in Delhi. *International Journal of Advanced Research*, *2*(1), 109–116. Retrieved from http://www.journalijar.com

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas Production and Applications in the Sustainable Energy Transition. *Journal of Energy*, *2022*, 1–43. https://doi.org/10.1155/2022/8750221

Kalyani, K. A., & Pandey, K. K. (2014). Waste to energy status in India: A short review. *Renewable and Sustainable Energy Reviews*, *31*, 113–120. https://doi.org/10.1016/j.rser.2013.11.020

Khairunnisa, A., Suryadi, A., Hufad, A., & Wahyudin, U. (2023). Waste Care Education for Housewives. *Jurnal Penelitian Pendidikan IPA*, *9*(10), 8217–8225. https://doi.org/10.29303/jppipa.v9i10.5272

Khan, I. (2020). Waste to biogas through anaerobic digestion: Hydrogen production potential in the developing world - A case of Bangladesh. *International Journal of Hydrogen Energy*, *45*(32), 15951–15962. https://doi.org/10.1016/j.ijhydene.2020.04.038

Khushboo, Ankush, Yadav, K., Mandal, M. K., Pal, S., Chaudhuri, H., & Dubey, K. K. (2020). Bioeconomy of municipal solid waste (MSW) using gas fermentation. In *Current Developments in Biotechnology and Bioengineering* (pp. 289–304). Elsevier. https://doi.org/10.1016/B978-0-444-64321-6.00015-X

Kim, Y. S., Jang, J. Y., Park, S. J., & Um, B. H. (2018).

Dilute sulfuric acid fractionation of Korean food waste for ethanol and lactic acid production by yeast. *Waste Management*, *74*, 231–240. https://doi.org/10.1016/j.wasman.2018.01.012

Knoef. (2012). *Handbook Biomass Gasification, 2nd Ed.* Enschede: BTG Biomass Technology Group.

Knox, A. (2005). *An Overview of Incineration and EFW Technology as Applied to the Management of Municipal Solid Waste (MSW)*. University of Western Ontario.

Kosseva, M. R. (2011). Management and Processing of Food Wastes. In *Comprehensive Biotechnology* (pp. 557–593). Elsevier. https://doi.org/10.1016/B978-0-08-088504-9.00393-7

Kothari, R., Tyagi, V. V., & Pathak, A. (2010). Waste-to-energy: A way from renewable energy sources to sustainable development. *Renewable and Sustainable Energy Reviews*, *14*(9), 3164–3170. https://doi.org/10.1016/j.rser.2010.05.005

Kumar, A., & Samadder, S. R. (2017). A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Management*, *69*, 407–422. https://doi.org/10.1016/j.wasman.2017.08.046

Lombardi, L., Carnevale, E., & Corti, A. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Manag*, *37*, 26–44. https://doi.org/10.1016/j.wasman.2014.11.010

Mahmoodi, P., Karimi, K., & Taherzadeh, M. J. (2018). Efficient conversion of municipal solid waste to biofuel by simultaneous dilute-acid hydrolysis of starch and pretreatment of lignocelluloses. *Energy Conversion and Management*, *166*, 569–578. https://doi.org/10.1016/j.enconman.2018.04.067

McKendry, P. (2002). Energy production from biomass (part 2): conversion technologies. *Bioresource Technology*, *83*(1), 47–54. https://doi.org/10.1016/S0960-8524(01)00119-5

Melville, L., Weger, A., Wiesgickl, S., & Franke, M. (2014). Anaerobic Digestion. In *Transformation of Biomass* (pp. 31–59). Wiley. https://doi.org/10.1002/9781118693643.ch2

Mujiarto, S., Sudarmanta, B., Fansuri, H., & Saleh, A. R. (2021). Comparative Study of Municipal Solid Waste Fuel and Refuse Derived Fuel in the Gasification Process Using Multi Stage Downdraft Gasifier. *Automotive Experiences*, *4*(2), 97–103. https://doi.org/10.31603/ae.4625

Muliarta, I. N., Hariani, C. Y., Wahyuni, N. M. I., & Rismayanti, A. . T. (2023). Study of Potential Food Waste in Zero Waste Cities Area- Saridewi, Denpasar-Bali. *Jurnal Penelitian Pendidikan IPA*, *9*(5), 2595–2603. https://doi.org/10.29303/jppipa.v9i5.3019

Nasir, I. M., Ghazi, T. I. M., & Omar, R. (2012). Production of biogas from solid organic wastes through anaerobic digestion: a review. *Applied Microbiology and Biotechnology*, *95*(2), 321–329. https://doi.org/10.1007/s00253-012-4152-7

Novita, D. M., & Damanhuri, E. (2010). Jurnal Teknik Lingkungan. *Jurnal Tehnik Lingkungan*, *16*(2), 103–115. https://doi.org/10.5614/jtl.2010.16.2.1

Pavlas, M., Touš, M., Klimek, P., & Bébar, L. (2011). Waste incineration with production of clean and reliable energy. *Clean Technologies and Environmental Policy*, *13*(4), 595–605. https://doi.org/10.1007/s10098-011-0353-5

Pham, T. P. T., Kaushik, R., Parshetti, G. K., Mahmood, R., & Balasubramanian, R. (2015). Food waste-to-energy conversion technologies: Current status and future directions. *Waste Management*, *38*, 399–408. https://doi.org/10.1016/j.wasman.2014.12.004

Prarikeslan, W., Nora, D., Mariya, S., Lovani, D., & Pratama, V. A. (2023). Community Empowerment through Organic Waste Processing. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 9447–9453. https://doi.org/10.29303/jppipa.v9i11.5448

Qanaze, M., & Qaffaf, H. (2021). *Biochar From Municipal Solid Waste (MSW)*. An-Najah National University, Faculty of Engineering and Information Technology, Energy and Environment Engineering Department. Retrieved from https://repository.najah.edu/bitstreams/bd95c1c0-5b1c-40e5-a937-0a04479dac3a/download

Qazi, W. A., Abushammala, M. F., & Azam, M.-H. (2018). Multi-criteria decision analysis of waste-to-energy technologies for municipal solid waste management in Sultanate of Oman. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *36*(7), 594–605. https://doi.org/10.1177/0734242X18777800

Rahma, A. N., Abbas, H. H., & Gafur, A. (2023). Konsentrasi Gas Amoniak (Nh3) Dan Gangguan Kesehatan Pada Pemulung Di TPA Tamangapa Kota Makassar. *Journal of Aafiyah Health Research (JAHR)*, *4*(2), 1–7. https://doi.org/10.52103/jahr.v4i2.1535.

Ramadhan, M. R. S., Ikhsan, M., Putra, R. M., Simatupang, J. W., Mau, S., & Kaburuan, E. R. (2021). Waste-to-Energy Potential Using Municipal Solid Waste as One Implementation of Jakarta Smart City. *Jurnal Serambi Engineering*, *6*(4), 2382–2394. https://doi.org/10.32672/jse.v6i4.3499

Rusman, R. S., Syafri, S., & Ridwan, R. (2023). Evaluasi Lokasi Tempat Pemrosesan Akhir (TPA) Antang Perubahan Pemanfaatan Ruang Disekitarnya. *Urban and Regional Studies Journal*, *5*(2), 87–91. https://doi.org/10.35965/ursj.v5i2.2690

Seo, Y.-C., Alam, M. T., & Yang, W.-S. (2018).

Gasification of Municipal Solid Waste. In *Gasification for Low-grade Feedstock*. InTech. https://doi.org/10.5772/intechopen.73685

Septianingrum, D., Mizuno, K., & Herdiansyah, H. (2023). Extended Producer Responsibility for Waste Management Policy. *Jurnal Penelitian Pendidikan IPA*, *9*(5), 2686–2692. https://doi.org/10.29303/jppipa.v9i5.3469

Setiawan, A. (2021). Membenahi Tata Kelola Sampah Indonesia. In *Indonesia.Go.Id*. Retrieved from https://indonesia.go.id/kategori/indonesia-dalam-angka/2533/membenahi-tata-kelola-sampah-nasional

SIPSN. (2021). *Sistem Informasi Pengelolaan Sampah Nasional*. Retrieved from https://sipsn.menlhk.go.id/sipsn/.

Stuckl, M., Jungbluth, N., & Leuenberger, M. (2012). Life Cycle Assessment of Biogas Production from Different Substrates. *ESU-Services Ltd.*, 1–84. Retrieved from https://esu-services.ch/fileadmin/download/publicLCI/stucki-2011-biogas-substrates.pdf

Sun, C., Li, W., Chen, X., Li, C., Tan, H., & Zhang, Y. (2021). Synergistic interactions for saving energy and promoting the co-pyrolysis of polylactic acid and wood flour. *Renewable Energy*, *171*, 254–265. https://doi.org/10.1016/j.renene.2021.02.099

Wang, L. J. (2013). Production of Bioenergy and Bioproducts from Food Processing Wastes: A Review. *Transactions of the ASABE*, *56*(1), 217–230. https://doi.org/10.13031/2013.42572

Yunus, M. (2012). *TPA Tamangapa Antang Terbakar, Api Semakin Membesar*. Suara.Com. Retrieved from https://sulsel.suara.com/read/2021/08/12/200202/tpa-tamangapa-antang-terbakar-api-semakin-membesar

Zhou, J., Chen, Q., Zhao, H., Cao, X., Mei, Q., Luo, Z., & Cen, K. (2009). Biomass–oxygen gasification in a high-temperature entrained-flow gasifier. *Biotechnology Advances*, *27*(5), 606–611. https://doi.org/10.1016/j.biotechadv.2009.04.011