Municipal solid waste-to-energy potential in DI Yogyakarta, Indonesia

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Abstract. This study presents current regional municipal waste management and Waste-to-Energy (WtE) technologies to help answer the challenges. While most of the solid municipal waste in the region is still disposed of in landfills, it has some potential to be converted into energy or electricity. Important data such as municipal waste management regulation, waste generation, compositions, and WtE potential conversion are collected and collated to present a comprehensive discussion regarding the issue. The daily waste production in DI Yogyakarta ranges from 360 to 470 tons, which is mostly comprised of organic waste. Four WtE technologies — conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis — have the potential to convert this waste into electricity, generating between 0.80 and 9.86 MW, and if operated continuously, could result in an annual electricity production of 7 to 86 GWh for the region. Among the four technologies, incineration is the most mature but has issues with harmful gas emissions. Anaerobic digestion produces cleaner gas but is limited to livestock manure and industrial biomass waste. Advanced gasification achieved the highest energy conversion but is less developed than the other WtE technologies.

1 Introduction

The solid waste management situation in Yogyakarta, Indonesia, presents a dire and complex challenge. As one of Indonesia's most populous regions and a cultural and economic activity hub, Yogyakarta grapples with significant issues related to solid waste generation, collection, and disposal. Rapid urbanization, population growth, and changing consumption patterns have exacerbated the strain on existing waste management infrastructure, leading to overflowing landfills, illegal dumping, and environmental degradation. In 2017, studies showed that the solid waste production in the province could reach as high as 470 tons per day, which is comprised mainly of organic waste [1,2]. Another study shows that the number was approximately 131.69 kilotons in 2020, meaning the average daily waste production was 360.79 tons per day [3]. Inadequate waste segregation practices, coupled with limited recycling and composting facilities, further compound the problem, contributing to pollution of waterways, soil contamination, and threats to public health.

In some high-income countries, waste-to-energy (WtE) technologies have become suitable. In this concept, solid waste is utilized as an alternative energy source to detain landfill area expansion, waste volume and quantity, and the cost of waste transportation [4]. Although Yogyakarta is considered one of the lowest-income regions in the country [5]. This study aims to review the WtE potential, which is currently being neglected as most solid waste is dumped in landfills. Four types of technologies, conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis, are reviewed and compared. In addition, their risks and issues are also discussed further below.

Previous studies on WtE technologies have been conducted in several countries and regions [6-10]. Overall, waste management poses an escalating difficulty across nations. Governments have implemented diverse policies to address this challenge, with differing levels of success. Several approaches have been explored to diminish landfill accumulation, such as recycling and WtE technologies. Incineration remains prevalent, primarily due to its perceived efficacy. To the best of the authors' knowledge, limited studies are still available on DI Yogyakarta province with its unique features.

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2 Current state of solid waste in Yogyakarta

Yogyakarta solid waste management relies heavily on Piyungan TPST (Integrated Waste Management Site) [3,4], although minor portions are also being disposed of in other locations. In the last few years, there have been frequent closures on the site [11] which has been predicted before by the unmatched rapid growth of waste generation in the region and Piyungan's capacity [1]. In the last report in June 2024, approximately 5,000 tons of waste were spread in several waste posts in Yogyakarta, which should have been sent to Piyungan. Health concerns also rise as the waste generates hazardous leached water and pathogenic larvae/maggots [12].

The waste composition (based on wet weight percentage) is presented in **Fig. 1** below. From the data, organic waste makes up most of Yogyakarta's waste 61.1 % (wet-based). Plastics and glass waste come next with approximately 10.7 and 10.8 %, respectively. It is essential to mention that it is difficult to present exact numbers of waste composition data in Yogyakarta, as the characteristics and properties of waste can vary from one place to another. The presented data below are based on the theoretical composition of waste from Piyungan site, which is considered the main dump site in Yogyakarta [3].

Source: [3]

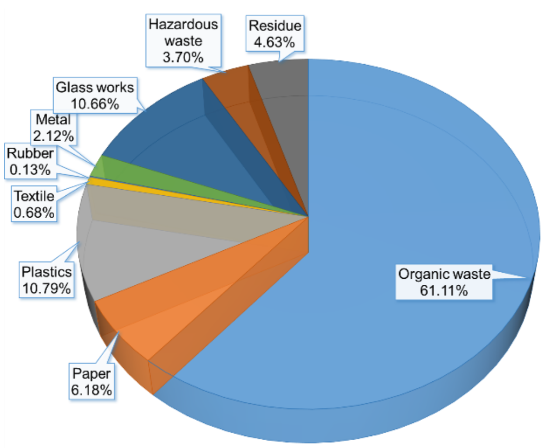

Fig. 1. Solid waste composition in DI Yogyakarta. Source: [3]

At the moment, the waste management plans in the regencies/ municipality in the province of Special Region of Yogyakarta are mainly governed by the local regulation (Peraturan Daerah/ PERDA), which was updated in 2022 [13]. The aim of the statute is to protect the environment in the region from harm while at the same time providing environmental, social, and economic benefits to the locals. Several measures are stated, which are [13]:

1. Reducing waste production by systematically reusing and recycling methods.
2. Sorting of waste by their type, starting from an individual level. Waste should be categorized into five categories: (a) hazardous and toxic waste, (b) easily decomposed waste, (c) reusable waste, (d) recyclable waste, and (e) other waste.
3. Compensation for whoever is impacted by waste management activities.
4. The incentive for whoever contributed to the development of waste management, which can be done via (a) technological innovation, (b) a report on wrongful waste management, (c) waste reduction, and (d) orderly waste management.

Although many impactful regulations have been published in the statute, the actual implementation of the regulations is the main concern because the dire conditions of waste in the region do not represent the statute in any manner. On the other hand, nation-wise, the Indonesian government has mandated the acceleration of the WtE plant application through Presidential Regulation No35/2018 [14].

Regarding waste treatment, landfills remain the go-to option for throwing away most of our solid rubbish. One of many reasons is that there is still limited study and discussion about alternative techniques, including various WtE options. From four different technologies (conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis), incineration is the most technologically mature option [8].

To understand the amount of energy contained in the municipal waste in Yogyakarta, **Table 1** presents the calculation based on the waste type, water content, and heating value of the waste type. The Heating value of each waste type is referred to in a previous study by Perrot and Subiantoro (2018) and is based on dry weight. The formulas to calculate the presented data in the table are:

$$Dry\ base\ wt. = total\ waste\ wt.\ \times (\%\ wet\ wt.) \times (100 - \%\ water\ content) = [\tfrac{ton}{day}] \quad (1)$$

$$Energy\ contained\ \left(\frac{GJ}{day}\right) = dry\ base\ wt.\ \left(\frac{ton}{day}\right) \times heating\ value\ (\tfrac{MJ}{kg}) \quad (2)$$

This calculation shows that the total energy contained in DI Yogyakarta's municipal waste is approximately 2,156.56 GJ/day.

From this result, four different WtE technologies, conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis, and their conservative energy conversion efficiencies (21.00%, 10.40%, 35.00%, and 20.50%, respectively) are compared, as shown in **Table 2**. By multiplying these efficiencies by the contained energy, the resulting potential energy generated from the technologies is 5.92, 0.80, 9.86, and 5.78 MW for conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis, respectively. Considering that the waste production can run consistently throughout the year, this would mean the region's electricity generation of 7 to 86 GWh/year.

Table 1. Potential contained energy from municipal solid waste in DI Yogyakarta.

Composition	% Wet Weight	Water content, wt%	Amount of waste (dry base), ton/day	Heating value, MJ/kg. Source: [15]	Energy contained, GJ/day
Organic waste	61.1	37.6	137.60	3	412.80
Paper	6.2	5.9	20.98	16	335.70
Plastics	10.8	0.4	38.77	35	1,357.08
Textile	0.7	8.9	2.24	19	42.47
Rubber	0.1	1	0.46	14	6.50
Metal	2.1	0.2	7.63	0	-
Glassworks	10.7	0.02	38.45	0	-
Hazardous waste	3.7	4.2	12.79	0	-
Residue	4.6	4.2	16.00	0	-
Total	100.0		360.83		2,156.56

Table 2. Energy generation potentials from municipal solid waste in DI Yogyakarta. Source: [15].

	Conventional incineration	Anaerobic digestion	Advanced gasification	Pyrolysis
Energy efficiency	21.00%	10.40%	35.00%	20.50%
Energy production potential, MW	5.92	0.80	9.86	5.78

These numbers are low compared to the electricity consumption in the area, which was 3,564.23 GWh in 2023 (equivalent to consuming electricity from a 406.8 MW power plant for 24 hours in 365 days for the whole year). However, according to the same report, DI Yogyakarta only has 0.78 MW of installed capacity in the region [16], meaning the majority of the electricity was purchased from neighboring regions. This figure shows that the WtE application in the region shows potential for the region to start generating electricity independently.

3 Waste-to-energy Technologies in Indonesia

As the majority of the solid waste in Indonesia goes to landfills, adopting WtE technology will become a sooner or later decision that the government has to make in the future. One of the biggest challenges is the capital investment for the plant to be built [9,10,14]. A relatively huge capital investment for the WtE application impacts the return time on the investment. In Indonesia, techno-economic studies reveal that the return rate varied between 8 to 25 %, meaning the capital investment will be repurchased in about 4 to 12 years. However, this approximation includes a good portion of tipping fees and electricity price [14]. However, it should be noted that this type of energy is not affected by seasons and has a relatively increasing raw material/ source each year.

3.1 Conventional incineration

Currently, incineration is the most mature technology for WtE applications [8]. The process involves burning waste in furnaces and utilizing the generated heat to produce electricity or heat. This results in by-products such as ash and exhaust gas. The ash can be further treated to extract metals for recycling, while the remaining material can be used in construction. Currently, most modern plants achieve an energy efficiency of about 30% [8] and the most common system is the steam-turbine generator, depicted in **Fig. 2** below.

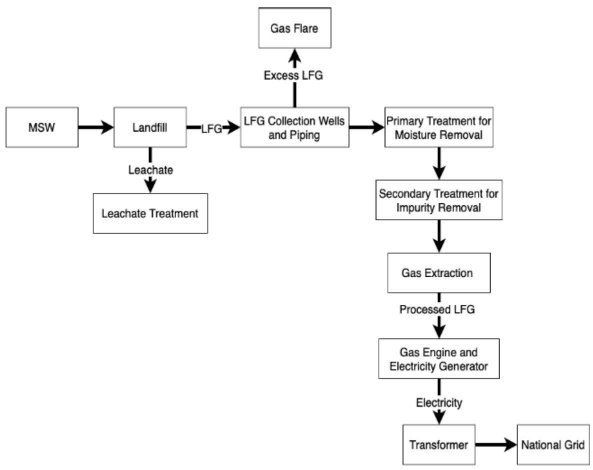

Fig. 2. Municipal Solid Waste (MSW) incineration flow diagram. Source: [17]

Recently, integrated waste-to-energy (WtE) gas turbine power plants have been proposed to boost energy efficiency by over 40%, with three such plants established in Spain, the Netherlands, and Japan by 2012 [18]. Although the technology is still developing, the integrated gas turbine system represents the future of WtE incineration technologies.

One of the most advantageous features of conventional incineration is its ability to reduce waste in terms of capacity and volume effectively [19]. One of the most successful cases of incineration is happening in Sweden. A lot of effort has been put into recycling, while the rest of the waste mostly being turned to energy via incineration (50%); Sweden only has 1% of their waste end up in landfills [15,20]. On the other side, its disadvantages are related to the cost and environmental issues [15]. With a population of approximately 3 million lives [5,21], there is a significant risk that the incineration plant will be built near the social communities in DI Yogyakarta. The incinerators can emit harmful and toxic gases such as CO, CO_2, dioxins, and heavy metals into the environment.

3.2 Anaerobic digestion

Anaerobic digestion is a technique to turn waste into energy involving the decomposition of organic materials using bacteria without the presence of air. The resulting gas from anaerobic digestion is often known as biogas (methane and carbon dioxide). The main advantage of this technique is cleaner energy, as the bacteria will not be able to process minerals, metals, and other inorganic matter, leaving them to stay in the liquid or solid state. This would also mean that this technique can bring plant nutrients back into the soil [22]. Globally, it was recorded that the installed biogas power plant unit generates almost 18 GW of electricity, with Germany, the United States, the United Kingdom, and Italy as the biggest producer countries [23]. It is, however, important to note that this technique is not the most mature method. From approximately 730 Mtoe (million tons of oil equivalent) of biomethane potential and 570 Mtoe of biogas potential, only 35 Mtoe (comprising only 6.1% of the potential) are actually being harnessed [23]. The simplified process and flow diagram of anaerobic digestion are provided in **Fig. 3 and 4** below.

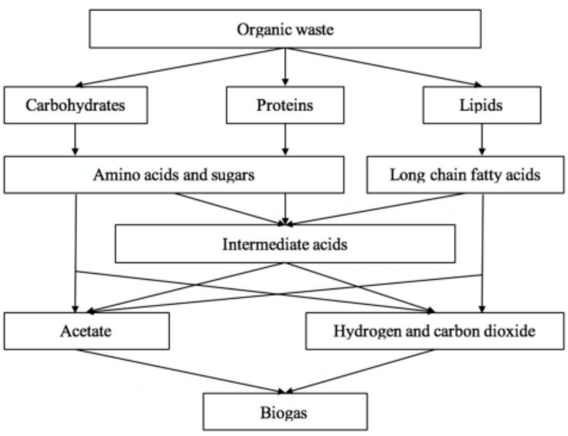

Fig. 3. Simplified process of anaerobic digestion. Source: [9,24]

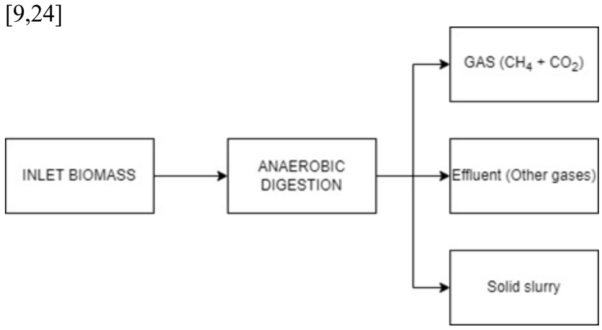

Fig. 4. Flow diagram of anaerobic digestion. Source: [9,24]

In Indonesia, much of the works on anaerobic digestion are focused on the waste management on livestock farms and slaughterhouse. It was estimated that, from livestock manure production alone, the potential for waste to energy via anaerobic digestion in Indonesia is 1.7 x 10^{10} kWh/year of electricity in 2016 [25]. Another potential was also reviewed from oil palm empty fruit bunches, as Indonesia is also the major producer of the commodity globally. However, this technique faces challenges to develop due to its considerably long and complex technical process and low economic value [25,26].

3.3 Advanced gasification

Advanced gasification is a process of turning waste into energy by converting organic compounds into a gas mixture and solid products that have heating values. Gasification is an essential technology for utilizing biomass, providing significant flexibility in the types of feedstock materials it can process and the range of products it can generate. All kinds of biomass can be gasified to produce syngas, mainly hydrogen, carbon monoxide, carbon dioxide, and methane. This syngas can then be used to produce various forms of energy or energy carriers, such as heat, power, biofuels, hydrogen, biomethane, and chemicals. Established technical processes include the synthesis of Fischer-Tropsch (FT) diesel, dimethyl ether (DME), methanol, and methane. Efficient and sustainable use of available biomass resources is crucial. Gasification has high potential and process efficiency for biomass utilization. This process involves partially oxidizing biomass carbon at high temperatures with a controlled amount of an oxidant, which could be air, pure oxygen, or steam. The syngas composition and properties depend on the biomass feedstock, the type of gasifier, and the gasifier's operating conditions, such as the oxidant used, temperature, and residence time. The gasification process occurs at temperatures between 750 to 1150 °C, depending on the type of the reactor, which also affects the composition of the produced syngas following its further application or needs [27]. Typical advanced gasification processes include drying, gasification, gas cleaning, condensation, and furnace/ gas turbine unit [28], as depicted in **Fig. 5**.

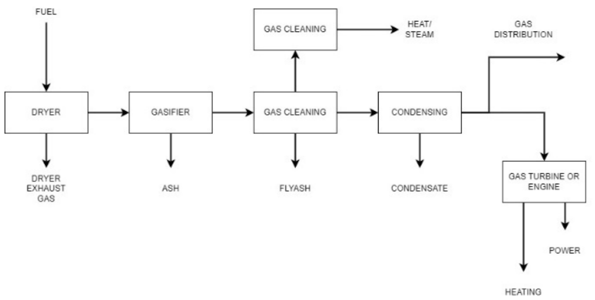

Fig. 5. Typical gasification process units. Edited from source: [28]

As depicted in the figure above, there is a similarity in gasification/ pyrolysis with incineration, that is, by applying heat to the solid waste. However, in gasification and pyrolysis, heat is a medium that transforms waste into fuel gas, which eventually powers the gas turbine. In incineration, steam is the working fluid that generates the power. In Indonesia, gasification is technically and economically feasible to be applied in abundant biomass resource locations, such as from the disposal site of oil palm wastes [29]. However, as far as the authors are concerned, there are still limited studies on municipal waste gasification processes.

3.4 Pyrolysis

Pyrolysis is a process similar to gasification but without oxygen. Pyrolysis produces charcoal (solid), bio-oil (liquid), and fuel gas products. The pyrolysis process can be categorized into three subclasses based on the operating conditions: conventional pyrolysis (also known as carbonization), fast pyrolysis, and flash pyrolysis [30], and the details of each type are given in **Table 3** below.

Table 3. Range of main operating parameters of pyrolysis. Source: [30]

	Conventional pyrolysis	Fast pyrolysis	Flash pyrolysis
Temperature (K)	550 – 950	850 – 1250	1050 – 1300
Heating rate (K/s)	0.1 - 1	10 – 200	> 1000
Particle size (mm)	5 – 50	<1	< 0.2
Solid residence time (s)	450 – 550	0.5 – 10	< 0.5

The Waste-to-Energy (WtE) potential pyrolysis efficiency is comparable to gasification, and both methods can process all types of municipal waste. However, these technologies are less developed compared to anaerobic digestion and incineration [31].

3.5 Comparison matrix

From an environmental perspective, several key metrics can be considered to compare incineration, anaerobic digestion, advanced gasification, and pyrolysis waste-to-energy (WTE) technologies: greenhouse gas (GHG) emissions, waste reduction potential, and pollutants. For incineration, GHG emissions are approximately 700–1,200 kg CO_2 (eq.)/ton of waste processed, depending on the efficiency and pollution control measures. The waste reduction is up to 80–90% by mass, but it leaves behind ash (fly ash and bottom ash), some of which can be hazardous. In addition, there is high concern for dioxins, furans, NOx, SOx, and particulate matter (PM) [32]. For anaerobic digestion, the GHG emissions are approximately 40–176 kg CO_2 (eq.)/ton of waste, as the process involves capturing methane (CH_4) for energy use, a gas 25 times more potent than CO_2. In addition, it has minimal NOx or SOx emissions [33]. However, the volume reduction is only 50 to 70%. In advanced gasification, the GHG emissions are 75–890 kg CO_2 (eq.)/ton (depending on efficiency), with a 75 to 90% volume reduction. This technology has moderate pollutant control. Emissions of NOx, CO, and trace metals are lower than incineration because it operates at lower temperatures with controlled oxidation [34,35]. In pyrolysis, the GHG emissions: 75–600 kg CO_2 (eq.)/ton, with similar volume reduction and other emissions with gasification [35]. The matrix is given in **Table 4** below.

Table 4. Comparison of critical metrics in WtE technologies.

Technology	GHG (kg CO_2e/ton)	Waste Reduction (%)	Pollutants (concern)
Incineration	700–1,200	80–90	High (dioxins, NOx, PM)
Anaerobic Digestion	40–176	50–70	Low (minimal air pollutants)
Advanced Gasification	75–890	75–90	Moderate (NOx, CO)
Pyrolysis	75–600	70–90	Low (NOx, lower dioxins)

Additionally, a rank-based matrix comprising energy efficiency/ conversion, flexibility of raw materials, environmental impact, and technological maturity is provided in **Table 5** below. The numbers in the matrix represent the rank between the four WtE technologies that are being compared. Therefore, a smaller scale generally represents an overall better condition. From this matrix, conventional incineration (CI) comes as the best option, followed by advanced gasification (AG), anaerobic digestion (AD) and pyrolysis (P).

Table 5. Ranking comparison of four WtE technologies.

WtE technology	CI	AD	AG	P
Energy efficiency	2	3	1	2
Flexibility of raw material	1	3	2	2
Environmental impact	3	1	2	2
Technology maturity	1	2	3	3
Total	**7**	**9**	**8**	**9**

4 Conclusion

This study has discussed and compared the potential of four different waste-to-energy technologies to help manage waste in the DI Yogyakarta context. The DI Yogyakarta's daily waste production ranges from 360 to

470 tons, which poses many health and socio-economic risks. From four different WtE technologies, the potential energy that can be converted into electricity ranges from 0.80 to 9.86 MW. If running continuously, this figure would mean the region's electricity generation of 7 to 86 GWh annually. Although this result is low compared to the region's electricity consumption (3,326.61 GWh in 2023), the WtE application still shows some potential.

Of four technologies (conventional incineration, anaerobic digestion, advanced gasification, and pyrolysis), the most technologically mature technique is conventional incineration. However, the technology has some issues related to gas emissions, which may be harmful to the communities in the region. Studies on anaerobic digestion offer cleaner gas products, but the raw material of the process is only focused on livestock manure and industrial biomass wastes. The highest energy conversion was achieved by advanced gasification, but the technology is less mature than the previous WtE technologies.

The authors of this study are inspired by the study of Perrot and Alison (2018) entitled, "*Municipal Waste Management Strategy Review and Waste-to-Energy Potentials in New Zealand*".

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