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JURNAL ILMU LINGKUNGAN
Volume 21 Issue 3 (2023) : 581-593 *ISSN 1829-8907*

Technical, Economic, and Environmental Review of Waste to Energy Technologies from Municipal Solid Waste

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ABSTRAK

Produksi sampah (MSW) dan permintaan listrik global secara bertahap meningkat sebagai akibat dari urbanisasi, peningkatan populasi, dan pertumbuhan ekonomi. Pemilihan teknologi konversi sampah menjadi energi (WTE) yang tepat perlu mempertimbangkan aspek efisiensi energi, finansial, dan lingkungan. Artikel ini membahas sisi teknis, finansial, dan lingkungan dari teknologi WTE yang ada. Teknologi konversi sampah menjadi energi (WTE) meliputi teknologi termal, fisika, biokimia, dan bio-elektrokimia. Pirolisis, gasifikasi, dan insinerasi merupakan teknologi termal yang digunakan untuk menghasilkan energi dari sampah berupa panas dan syn-gas. Anaerobik digestion dan landfill merupakan teknologi biokimia untuk menghasilkan energi dari sampah berupa biogas. Teknologi fisika digunakan untuk menghasilkan energi dari sampah berupa refuse-derived fuel (RDF). Microbial fuel cells (MFC) dan microbial electrolysis cells (MEC) adalah teknologi WTE terbaru yang menghasilkan listrik dan bahan bakar hidrogen. Hasil penilaian terhadap teknologi WTE yang ada menunjukkan bahwa anaerobik digestion dan landfill adalah teknologi WTE berbiaya rendah tetapi memiliki potensi produksi energi yang rendah. Gasifikasi plasma adalah teknologi WTE dengan potensi untuk produksi energi, cold gas efficiency (CGE), carbon conversion efficiency (CCE), dan rasio H_2/CO yang tinggi, emisi CO_2 rendah, dan biaya operasi yang tinggi. MEC memiliki potensi energi dari H_2 yang tinggi, emisi CO_2 rendah, dan biaya investasi tertinggi. Insinerasi adalah teknologi konversi yang umum dengan potensi energi yang rendah, emisi CO_2 yang tinggi, dan biaya investasi yang tinggi. Pemilihan teknologi WTE dipengaruhi oleh faktor teknis, ekonomi, dan lingkungan.

Kata kunci: Sampah, Energi, Teknik, Ekonomi, Lingkungan

ABSTRACT

Global municipal solid waste production and electricity demand gradually increased as a result of urbanization, population increase, and economic growth. The appropriate selection of Waste to energy (WTE) technologies needs consideration of energy efficiency, financial, and environmental aspects. This article discusses the technical, financial, and environmental side of existing WTE technologies. Waste-to-energy (WTE) technologies include thermal, physical, biochemical, and bio-electrochemical technology. Pyrolysis, gasification, and incineration are thermal technology used to generate energy from waste in the form of heat and syn-gas. Anaerobic digestion and landfill are biochemical technology to to generate energy from waste in the form of biogas. Physical technology is used to to generate energy from waste in the form of refuse-derived fuel (RDF). Microbial fuel cells (MFC) and microbial electrolysis cells (MEC) are the most recent WTE technology that produces electricity and hydrogen fuel. The results of the assessment of existing technology show that anaerobic digestion and landfill are low-cost WTE technology but have a low potential for energy generation. Plasma gasification is WTE technology with a high potential for energy generation, cold gas efficiency (CGE), carbon conversion efficiency (CCE), and H_2/CO ratio, low CO_2 emissions, and high operating costs. MEC has a high H_2-potential for energy generation, low CO_2 emissions, and the highest capital cost. Incineration is a common conversion technology with a low potential for energy generation, high CO_2 emissions, and high capital costs. The selection of WTE technologies is influenced by technical, economic, and environmental factors.

Keywords: municipal solid waste, energy, technical, economic, environmental

Citation: Jamilatun, S., Pitoyo, J., dan Setyawan, M. (2023). Technical, Economic, and Environmental Review of Waste to Energy Technologies from Municipal Solid Waste. Jurnal Ilmu Lingkungan, 23(3), 581-593, doi:10.14710/jil.21.3.581-593

1. Introduction

Economic growth, industrialization, urbanization, and high standards of living have led to a rapid increase in demand for energy, thereby increasing the global municipal solid waste (MSW) production (Kaur et al., 2021). According to World Bank statistics, MSW produced worldwide reached 2.01 billion tonnes in 2016 and this is predicted to increase above 3.4 billion tonnes per year by 2050 (Kaza et al., 2021). Meanwhile, waste production in

Indonesia reaches 19.45 million tonnes per year with a composition of food waste, plastic, wood, metal, glass, cloth or fabric, leather, and rubber as shown in Figure 1.

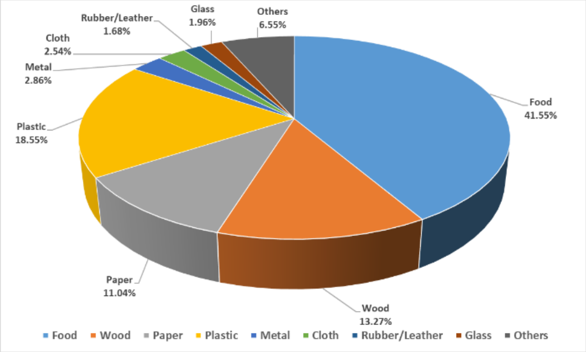

Figure 1. Indonesia's waste composition in 2023. (Source: adapted from www.sipsn.menlhk.go.id)

On the other hand energy demands still rely on fossil fuels which cause negative impacts on the environment, namely increasing greenhouse gas emissions. Therefore eco-friendly alternative energy resources are needed to provide for the global energy demand. The issue of MSW accumulation and the demand for alternative energy can be solved by utilizing energy from MSW. The process of utilizing energy from MSW is called Waste to Energy (WTE). Literature reviews related to WTE technology have been carried out by previous researchers. Beyene et al. (2018) discussed the current updates of WTE technology. Kaur et al. (2021) discuss the advantages and drawbacks of WTE technology. Giusti et al. (2009) discussed the effects of waste management procedures on human health. Roy et al. (2022) discussed the characteristics, methods, and waste-to-energy aspects of MSW management in Bangladesh. These reviews only address technical issues and are partly based on local perspectives, therefore it is important to conduct a comprehensive review related to the existing WTE technology, technical, economical, and environmental aspects of existing WTE technology. This article review aims to discuss the existing WTE technologies, the technical, the economic, and the environmental aspect of existing technologies.

2. Waste to Energy

2.1. Municipal solid waste (MSW)

Municipal solid waste (MSW) is all useless, unwanted, and discarded materials that result from people's daily activities that come from households, industries, schools, offices, shops, and others. The quantity, composition, and characteristics of MSW vary in each country depending on the rate of population growth, income, urbanization (Kaza et al., 2021), collection methods, and lifestyle (Rezaei et al., 2018). Table 1 shows the characterization of MSW.

2.2 Waste to Energy Technologies

The amount, composition, and characteristics of waste vary in each country depending on population growth rates, income, urbanization flows (Kaza et al., 2021), collection methods and lifestyle (Rezaei et al., 2018). Based on the composition of the waste, several alternative treatments can be carried out. Combustible materials with low to high calorific values such as plastic, paper, cloth, and wood are converted into energy with WTE technology. Non-combustible materials such as metals and glass are recycled if they are of economic value or disposed of in landfills. Some combustible materials such as paper, board, and plastic are also recycled. The heating value of combustible materials can be increased by an energy densification step. Materials that are dry or have a low water content are processed thermally, while materials with a high water content such as food waste, yard waste, and wood are processed biochemically or composting. Landfills are the last resort and are only used after the waste has been reduced, either by recycling or by converting it through WTE technology. Figure 2 shows a flowchart in determining the technology to be used for waste processing.

The WTE technologies used in each country vary depending on climatic conditions, population, generated waste types, and geographical conditions (Edjabou et al., 2015). WTE technologies can be classified into physical, thermal, biochemical, and bio-electrochemical technology. Through physical technology, MSW is converted to fuel, namely Refused derived fuel (RDF). Thermal technology includes incineration or combustion, gasification, and

Table 1. Characteristics of municipal solid waste

Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Ultimate analysis (%)					Calorific value LHV (MJ/kg)	Ref.
				C	H	O	N	S		
8.6	24.42	52.21	24.48	22.78	5.92	46.73	0.28	0.07	11.48	(Beyene et al., 2018)
2.3	7.7	87	5.3	40.3	5.6	53	0.2	-	10.9	(Kim et al., 2012)
4.63	16.73	77.93	5.32	-	-	-	-	-	-	(Y. C. Chen, 2016)
70	29	71	9.05	-	-	-	0.89	-	25.32	(Alam & Qiao, 2020)
-	22.38	66.56	11.06	58.48	9.22	31.78	0.37	0.15	-	(H. He et al., 2021)
3.3	9.1	79.7	7.2	63.6	8.19	27	0.4	0.1	15.98	(Azam et al., 2020)

pyrolysis (Tomić et al., 2017). During this process heat and syn-gas are generated. Anaerobic digestion and landfill are part of the biochemical conversion technology. In this process, organic matter is converted micro-biologically into biogas in an oxygen-free environment. Microbial fuel cells (MFC) and microbial electrolysis cells (MEC) are the newest MSW processing methods that utilize the role of microbes to produce electricity and hydrogen fuel (Beyene et al., 2018). Figure 3 shows the various technologies for processing MSW into energy and the resulting products.

The following are existing technologies to convert waste to energy.

2.2.1. Physical conversion

Physical conversion is the process by which MSW is physically/mechanically processed into energy to produce fuel/RDF. This process includes screening, sorting, separation, shredding, and drying.

- Refuse Derived Fuel (RDF)

RDF is a fuel made from combustible materials in MSW such as non-recyclable plastic, paper, cardboard, and other combustible materials. RDF is an alternative to landfill and includes an environmentally friendly method. MSW produced from commercial and domestic activities is chopped, dried, separated by different processes such as screening, air classification, and ballistic separation, and then packaged in pellet form to obtain a homogeneous material (Kaur et al., 2021). RDF can be utilized as fuel in cement plants, lime factories, and power plants as a substitute for conventional fuels such as coal. The characteristics and heating value of RDF are shown in table 2 below.

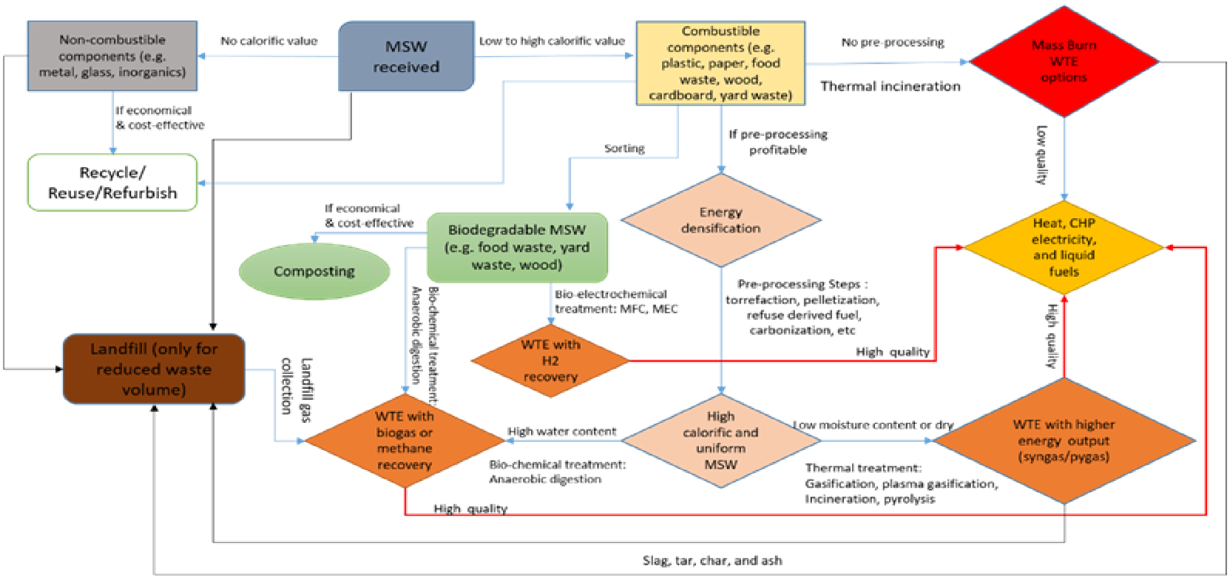

Figure 2. The selection of waste treatment technologies (Source: adapted from Mukherjee et al., 2020)

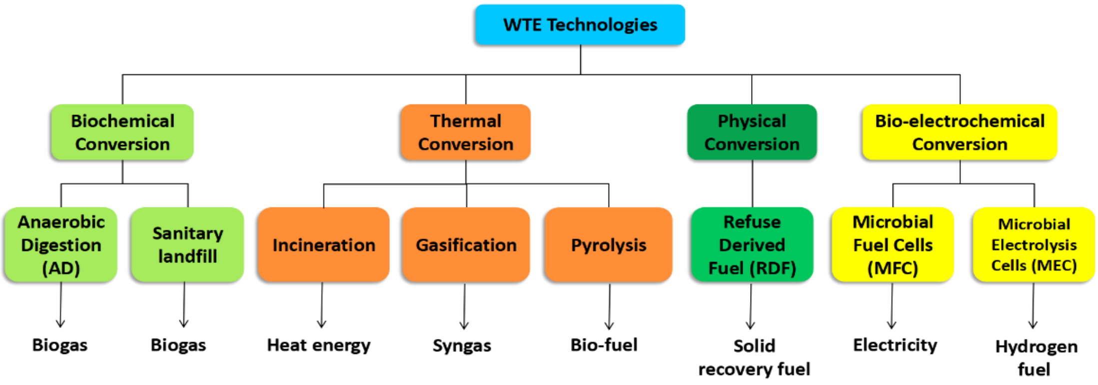

Figure 3. MSW processing technology into energy and the resulting product

Table 2. Characteristics of refuse-derived fuel (RDF)

Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Ultimate analysis (%)					Calorific value LHV (MJ/kg)	Ref.
				C	H	O	N	S		
5.8	13.7	71.6	13.8	49.4	6.7	28.1	0.3	1.0	16.89	(Beyene et al., 2018)
10-30	20-30	50-65	12-15	20-30	3-5	20-25	1-1.5	0.2-0.3	11.32	(Subramani & Murugan, 2014)

Table 3. Characteristics of biogas from MSW anaerobic digestion

CH_4 (%)	CO_2 (%)	O_2 (%)	Moisture content (%)	N_2 (%)	H_2 (%)	H_2S (ppm)	NH_3 (%)	Trace gas (%)	Calorific value LHV (MJ/Nm^3)	Ref.
40-75	15-60	<2%	1-5	0-5	-	0-5000	0-500	<2%	20.85	(Meng et al., 2015)
50-70	30-50	0-1	saturation	0-1	0-2	0.8	-	-	21.59	(Markoš, 2011)
50-80	30-50	0-1	saturation	0-1	0-2	0.7	-	-	23.38	(Markoš, 2011)

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Table 4. Characteristics of biogas from landfills

CH_4 (%)	CO_2 (%)	O_2 (%)	Moisture content (%)	N_2 (%)	H_2 (%)	H_2S (ppm)	NH_3 (%)	CO (%)	Calorific value LHV (MJ/Nm^3)	Ref.
50-80	20-50	<2%	saturation	0-3	0-5	0.1	-	<2%	23.67	(X. Y. Chen et al., 2015)
55-65	35-45	0-2	-	0-3	0-1	0.1	0-1	-	21.53	(Aich & Ghosh, 2016)

2.2.2. Biochemical conversion

Biochemical conversion is a methods in which organic materials are processed micro-biologically in an oxygen-free atmosphere to produce biogas. The main components of biogas are methane (CH_4) and carbon dioxide (CO_2). Anaerobic digestion and landfill are among the methods used to convert MSW into energy through biochemical processes. This process is carried out to treat MSW that has a high water content such as organic MSW and agricultural waste (Kaur et al., 2021).

- Anaerobic Digestion (AD)

Anaerobic digestion is a technique to decompose organic matter with the aid of anaerobic microorganisms under oxygen-free environment. In this process, sorting is carried out to separate metal, glass, and plastic from the organic materials in MSW so that the organic fraction of municipal solid waste (OFMSW) is obtained. OFMSW was then chopped, inserted, and kept in a bio-reactor under oxygen-free environment conditions and in the presence of acidogenesis and methanogenic microorganisms. The yield of methane produced depends on the operating conditions, MSW composition, reactor type, and residence time (Shah et al., 2021). Table 3 shows the characteristics of biogas produced from municipal solid waste (MSW).

- Landfill

The landfill is the conventional and simplest biological method to obtain energy from MSW. The landfill produces biogas which can be used for heating purpose and electricity generation. The amount of biogas produced depends on MSW composition, MSW age, water content, and temperature (Bharathiraja et al., 2018). Table 4 shows the characteristics of biogas in landfills .

2.2.3. Thermal conversion

In thermal conversion, municipal solid waste (MSW) is converted in the form of heat or syn-gas to obtain the energy. This energy can be utilized to produce steam for electricity generation. Thermal conversion includes incineration, gasification, plasma gasification and pyrolysis.

- Incineration

Incineration involves burning MSW at high temperatures (800-1000°C) in excess of oxygen. Incineration is common method in developing countries (Yong et al., 2019). Incineration can reduce MSW volume by as much as 80-90% (Y. Wang et al., 2018). Table 5 shows the characteristics of MSW incineration Gasification.

Gasification is a thermochemical method in which organic waste and carbon-containing waste materials are converted into syngas (Kaur et al., 2021). Gasification is a new technology in the WTE process that is widely used in developed countries (X. Y. Chen et al., 2015) and has an important role in energy production. The syngas consist of hydrogen, carbon monoxide, and methane as main components. The energy content of syngas is equivalent to one-third of the natural gas, which ranges from 4-50 MJ/Nm^3. There are several types of gasifiers such as continuous fluidized bed (CFB), bubbling fluidized bed (BFB), fluidized bed (FB), and others, each of which has its advantages, disadvantages, and operating characteristics. Table 6 shows several types of gasifiers.

- Plasma Gasification

Plasma gasification is a thermal conversion method to convert MSW into energy using an electric arc. Plasma is produced from the release of heat and light energy caused by the propagation of electricity through a non-conductive medium such as gas or air. Plasma gasification operated at 1400-2000 °C under partial oxidation to produce high-quality of syngas (Prado et al., 2020). The ratio of reducing the amount of waste in gasification plasma is 300:1, while in incineration is 5:1. Plasma gasification is carried out at high temperatures so can ensure the disappearance of harmful compounds, toxic compounds, bacteria, and deadly viruses and closed system so that ash, dust, and toxic compounds are not released in the outside environment. The electrical energy produced from the gasification process is cheaper and more efficient than incineration (Kaur et al., 2021).

- Pyrolysis

Pyrolysis is a new technology for WTE and is widely applied in developed countries (Meng et al., 2015). Pyrolysis can reduce MSW volume by 80-90%. Pyrolysis is an endothermic process in which heat is used to burn MSW in an oxygen-free environment. Pyrolysis produces three main products, namely pyro-oil in the form of a mixture of oil and water obtained from the condensation of steam, residue in the form of charcoal and ash which is rich in carbon content, and gas in the form of CO, CO_2, and methane (Jamilatun et al., 2022). Several factors influence pyrolysis including the pretreatment process, the composition of raw material, heating rate, temperature, residence time, and type of reactor (Pitoyo et al., 2022). Rotary kiln is the most used technique for pyrolysis of MSW (Hasan et al., 2021). Table 8 shows the characteristics of the gas from the pyrolysis.

2.2.4. Bio-electrochemical conversion

Bio-electrochemical conversion includes microbial fuel cells (MFC) and microbial electrolysis cells (MEC). This technology is the newest WTE technology that utilizes the role of microbes to produce hydrogen fuel and electricity.

- Microbial fuel cells (MFC)

Electrochemically active microorganisms (EAM) are used in MFC technology to produce electricity. MFCs involving both aerobic and anaerobic processes using bacteria as catalysts is a new approach to bio-hydrogen production. Various organic waste such as household waste, animal manure, and sewage sludge can be used as raw materials (Logroño et al., 2015). The use of organic waste makes MFC an eco-friendly technology that gives a dual purpose in waste management and bioelectricity generation (Xu et al., 2017). Table 9 shows electricity generation in different reactor designs and substrates.

- Microbial electrolysis cells (MEC)

MEC is a smart and green technology to face the challenges of global warming and meet energy demands. MEC works by utilizing electrochemically energetic bacteria to convert MSW into H_2 and chemicals (Kadier et al., 2017). Hydrogen production rate (HPR) in MEC is affected by the type of substrate, external voltage, electrode surface area, electrode spacing, membrane materials, and reactor design (Kadier et al., 2016). Compared to other non-conventional technologies, MEC has some advantages such as producing H_2 at low energy inputs, no need for precious metals on the anode of MEC, high conversion efficiency to hydrogen, producing relatively pure hydrogen, and producing other value-added products (Kadier et al., 2017). Table 10 shows the hydrogen production in MECs technologies from the literatures.

Table 5. Electricity and emission generation from MSW incineration

Power generated (kWh/Ton)	CO_2 (kg/Ton)	H_2O (kg/Ton)	N_2 (kg/Ton)	SO_x (kg/Ton)	NO_x (kg/Ton)	Particulate material (kg/Ton)	Ref.
584.95	978.28	132.39	2770.52	2.18	34.31	5.94	(Trindade et al., 2018)
614.03	978.28	132.39	2770.52	2.18	34.31	5.94	
485.55	310.96	-	-	-	-	-	(Tsai & Kuo, 2010)
497.6	318.47	-	-	-	-	-	

Table 6. Comparison of several types of gasifiers

Feed	Reactor	H_2O (%)	Operating conditions	LHV (MJ/Nm^3)	H_2 (%)	CO (%)	CGE (%)	Ref.
MSW	BFB	10	800 °C, air	5.4	16.0	24.0	62	(Kartal & Özveren, 2021)
MSW	FB	48	700 °C, air	5.8	43	42	-	(C. Chen et al., 2013)
MSW	CFB	51.7	900 °C, O2	6.174	28	25	88.9	(Shehzad et al., 2016)
MSW	FB	7.6	850 °C, air	5.43	6.9	18.8	40.3	(Cao et al., 2019)
MSW	FB	50.9	650 °C, air	6.37	24	30	54	(Ramzan et al., 2011)
MSW	BFB	-	687 °C, air	7	6.2	9.73	53	(Couto et al., 2015)

Table 7. Characteristics of gas from the plasma gasification process

CH_4 (%)	CO (%)	CO_2 (%)	HCl (%)	N_2 (%)	H_2 (%)	H_2S (ppm)	H_2O (%)	COS (%)	Calorific value LHV (MJ/Nm^3)	Ref.
-	37.37	1.41	0.31	17.12	28.65	0.22	14.19	0.01	7.80	(Galeno et al., 2011)
1.00	31.50	8.33	0.03	12.10	16.20	0.02	29.20	-	7.32	(Caroline Ducharme et al., 2010)
0.1	41.40	16.60	5.60	5.60	34.80	-	1.5	-	9.01	
-	41	4	-	14	33	-	8	-	8.73	
-	26	-			52		-		8.89	(Janajreh et al., 2021)
< 1	45.3	4.3			42.5		0.01		10.29	

Table 8. Characteristics of gas from the pyrolysis process

H_2 (%)	CO_2 (%)	CO (%)	CH_4 (%)	C_2H_4 (%)	C_2H_6 (%)	Calorific value LHV (MJ/Nm^3)	Ref.
52.53	12.21	29.05	17.45	3.5	5.26	10.58	(Sipra et al., 2018)
36.18	10.81	30.12	16.23	5.32	1.34	9.6	(M. He et al., 2010)
36.18	10.81	30.12	16.23	5.32	1.34	9.6	
40.80	16.85	25.01	9.80	2.45	5.09	7.26	(N. Wang et al., 2017)

Table 9. Electricity generation from MFCs

MFC design	Substrate	Power density (W/m^3)	Ref.
Single chamber	Wastewater	13.1	(Zuo et al., 2008)
Double chamber	Wastewater	2485	(Amend & Shock, 2001)
MFC-MBR	Wastewater	6.0	(Y. P. Wang et al., 2012)
-	Municipal wastewater	0.18	(F. Zhang et al., 2013)
-	Municipal wastewater	0.17	(Jiang et al., 2011)

Table 10. Hydrogen production in MECs

MEC design	HPR (m^3 H_2/m^3 d)	Ref.
Double chamber	1.5	(Selembo et al., 2009)
	50	(Jeremiasse et al., 2011)
Single chamber	1.1	(Cheng & Logan, 2007)
	3.4	(Lu & Ren, 2016)
	2.3	(Kadier et al., 2016)

3. Assessment of WTE technologies

3.1. Technical Assessment

3.1.1. Energy Generation from H_2

Hydrogen (H_2) is a green fuel, a high calorific value fuel that has the highest energy density. Hydrogen (H_2) has a calorific value of 120-142 MJ/kg. Figure 2 shows the potential for energy generation from H_2 among different WTE technologies. Bio-electrochemical technology, namely MEC has the highest, followed by thermal conversion and biochemical conversion technology. Bio-electrochemistry produces high purity of H_2 (up to 90%) (Khan et al., 2017), so it has a high H_2-potential for energy generation. Thermal conversion produces various gas compositions, namely CH_4, CO_2, CO, H_2, and others with H_2 content between 16-52%. Among the thermal conversion, incineration technologies have the lowest value because incineration is a combustion process that produces CO_2 and H_2O as the main gas composition (Thabit et al., 2022). Meanwhile, the biochemical conversion's gaseous product is mostly CH_4, CO_2, and a small amount of H_2 (0-5%) in composition (X. Y. Chen et al., 2015) so it has a low H_2-potential value.

3.1.2. Available Energy

Figure 3 shows available energy from waste which is the product of the lower heating value (LHV) of syngas and the volume of gas produced by the weight of waste in different WTE technologies. Available energy shows the potential for energy generation from waste. It can be seen from Fig. 3 that thermal conversion technology gives a greater value than biochemical conversion because thermal conversion produces a higher yield of syngas, which is 610-1240 m^3/ton (M. He et al., 2010), compared to biochemical conversion, which is 30-142 m^3/ton (Rahman et al., 2018). Plasma gasification produces the highest available energy value among thermal conversion technologies because plasma gasification has the highest LHV and syngas yield. The high LHV and yields of syngas provide greater available energy.

3.1.3. H_2/CO ratio

Figure 4 shows the H_2/CO ratio in various WTE technologies. H_2 and CO are diatomic molecules that provide the building blocks of fuel science and technology. The ratio of H_2/CO affects efficiency, combustion, and emissions. An increase in H_2/CO will increase thermal efficiency, combustion temperature, and NO_x emissions, and reduce HC and CO emissions (Sahoo et al., 2012). A high H_2/CO ratio (>2) is required in the Fischer-Tropsch synthesis (Zaccariello & Mastellone, 2015). It can be seen from Fig. 4 that pyrolysis produces a higher H_2/CO ratio than gasification. The high H_2/CO ratio is caused by the water-gas shift reaction that converts CO to H_2. Increasing the equivalent ratio (ER) in gasification, which is the ratio of actual oxygen to stoichiometric oxygen for complete combustion, will increase the oxidation of hydrogen to H_2O thereby reducing the H_2 content, and increase the oxidation of C and CO to CO_2 which further reacts with C through the Boudard reaction to produce CO thereby reducing H_2/CO ratio. Pyrolysis has an ER close to zero so it has a high H_2/CO ratio.

3.1.4. Cold gas efficiency (CGE)

Figure 5 shows the cold gas efficiency (CGE) of the three thermal conversion technologies (gasification, plasma gasification, and pyrolysis). CGE is the ratio between the calorific value of the syngas produced and the calorific value of the feedstock. CGE is related to the heat of combustion from syngas and feeds waste. CGE is a function of LHV and the volume/mass flow rate of syngas and feeds waste. The higher the LHV and the volumetric rate of syngas, the higher the CGE. The high value of CGE results in great combustion efficiency. Plasma gasification (PG) has a high CGE value compared to other thermal conversion technologies because PG takes place at high temperatures, resulting in a large volumetric rate of syngas. Plasma gasification can convert the volume of waste into syngas and slag up to about 99% (Prado et al., 2020).

3.1.5. Carbon conversion efficiency (CCE)

Figure 6 shows the carbon conversion efficiency (CCE) in three thermal conversion technologies (gasification, plasma gasification, and pyrolysis). CCE is defined as the amount of carbon in the waste which is converted to carbon in the syngas in the form of CO, CO_2, CH_4, C_2H_6, C_3H_8, etc. The CCE indicates how much of the unconverted waste should be treated by another process. CCE also indicates the chemical efficiency of the process (Seo et al., 2018). CCE is a function of carbon fraction and volumetric/mass flow rate of syngas and feeds waste. Plasma gasification (PG) provides the highest CCE value because the high temperature in PG produces a large volumetric rate of syngas, thereby increasing the conversion of carbon from waste to syngas.

3.2. Environmental Assessment

Figure 7 shows the emission factors for various WTE technologies. The emission factor shows how much CO_2 is released to produce a certain amount of energy from waste. CO_2 is the main component of greenhouse gas (GHG). It can be seen from the figure that incineration gives the highest emission factor between 0.6-1.1 tons/MWh, followed by gasification (0.2 tons/MWh), anaerobic digestion, and the landfill (0.12 tons/MWh), plasma gasification and pyrolysis (0.08 tons/MWh).), then MFC and MEC (close to zero). The high content of CO_2 in incineration is because incineration is a combustion process that produces CO_2 and H_2O as the main components in the gas (Thabit et al., 2022).

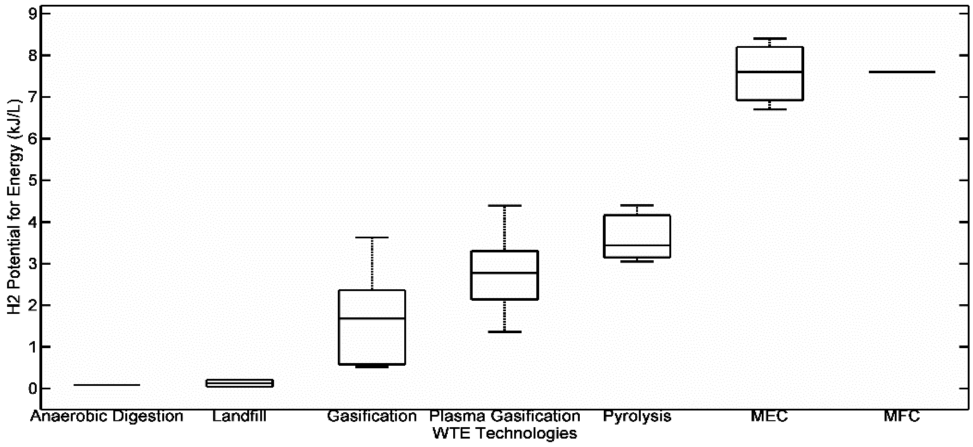

Figure 4. Potential for energy generation from hydrogen in different WTE technologies

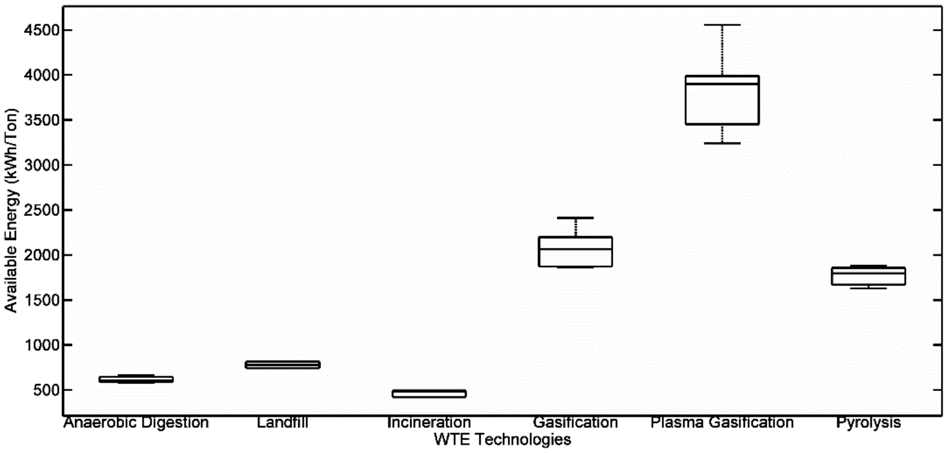

Figure 5. Available energy from waste through different WTE technologies

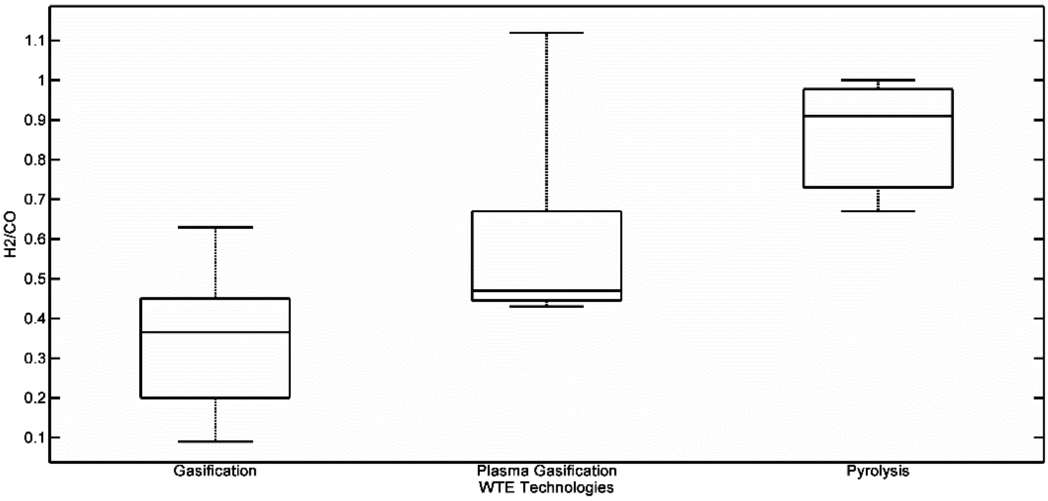

Figure 6. H2/CO ratio among different WTE technologies

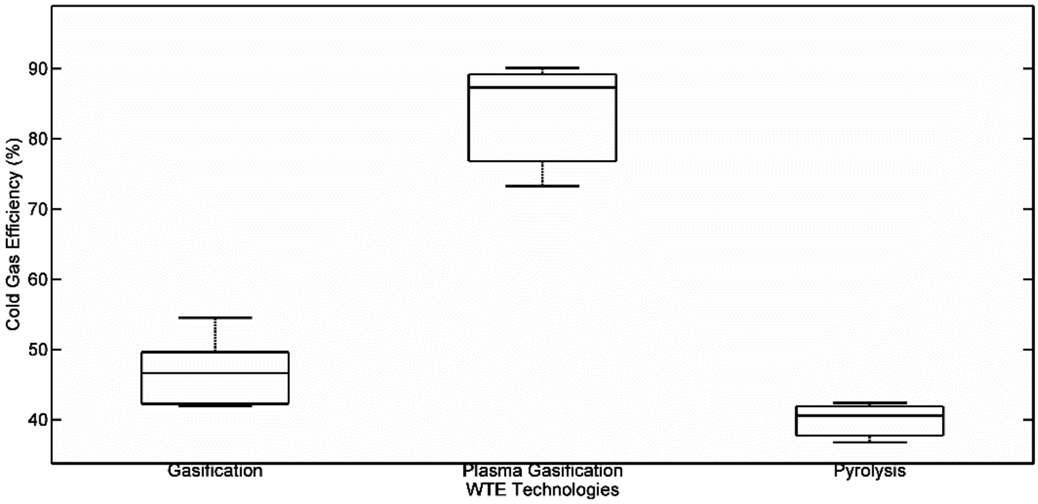

Figure 7. Cold gas efficiency (CGE) among different WTE technologies

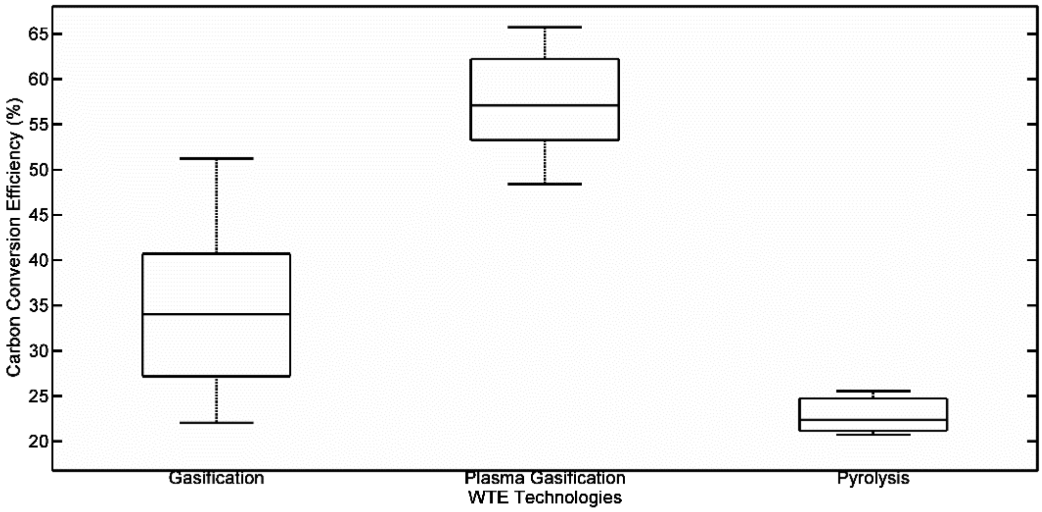

Figure 8. Carbon conversion efficiency (CCE) among different WTE technologies

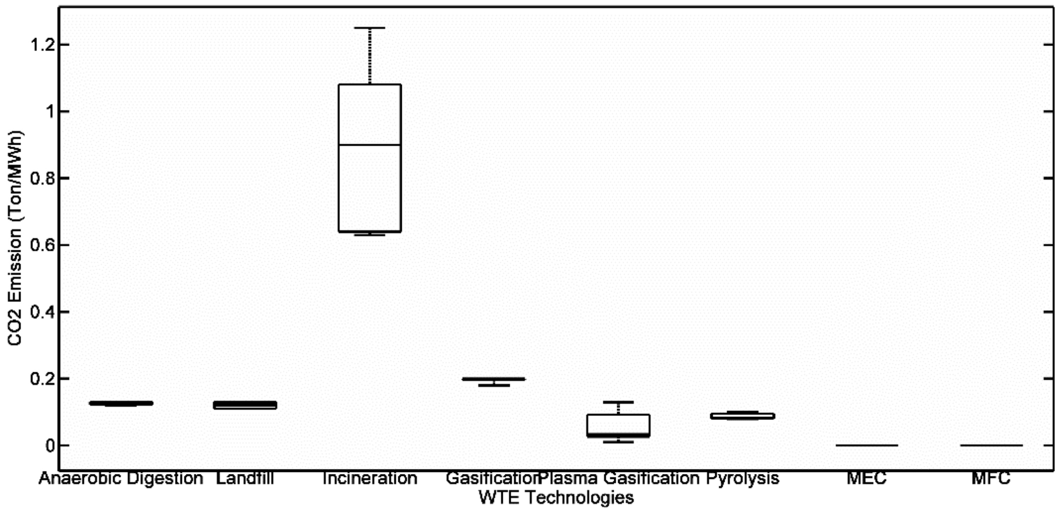

Figure 9. Emission factor among different WTE technologie

Table 11. Comparison of investment costs between WTE and non-WTE technologies

Technology for Energy Production			Estimated Capital Investment, $/kW	Ref.
Non-WTE technologies		Oil/gas power plant	950-1000	(US Energy Information Administration, 2022)
		Onshore wind	1850	
		Offshore wind	5500	
		Solar thermal	7100	
		Solar photovoltaic	1200-1600	
		Geothermal	2800	
		Advanced Nuclear	6400-6800	
		Combustion turbine with NG	700-1200	
		Fuel cell	7000	
		Cogeneration with coal	1700	(Li et al., 2014)
		Integrated gasification combined cycle with coal (IGCC)	1700	
		IGCC with carbon capture	1570	
WTE technologies	Conventional	Biomass	4100	(US Energy Information Administration, 2022)
		Landfill	1600	
		Anaerobic digestion (AD)	3700-7000	(Huiru et al., 2019)
	Non-conventional	Incineration	7000-10000	(Tangri, 2017)
		Pyrolysis	8000-11500	
		Gasification	7500-11000	
		Plasma gasification	8000-11500	
		MFC	14700	(Nasrabadi & Moghimi, 2022)
		MEC	39600	(Lu & Ren, 2016)

3.3. Economical Assessment

The cost of energy production is a main factor in the choice of WTE technology. Table 11 shows a comparison of investment costs between conventional technology and WTE technology. Table 11 shows that the average investment cost for energy production technology from MSW is relatively higher than that of other renewable and non-renewable resources, especially for non-conventional WTE technology (Tangri, 2017). These make conventional WTE technologies such as AD, landfill, and composting preferred because of the risk of cost, investment capital, and lower operating costs, especially in developing countries.

Operational and maintenance costs related to WTE technology are shown in table 12. Operational costs include labor, overhead, insurance, depreciation, and utility costs. Operational and maintenance costs on non-conventional WTE technology are higher than on conventional technology. Operational and maintenance costs are influenced by several parameters including socio-economic status, labor wages, high-efficiency targets, taxes, and insurance (Austin, 2013).

Table 12. Comparison of operational and maintenance costs on WTE technology

WTE TECHNOLOGY FOR ENERGY PRODUCTION		O & M COST USD/TONNE OF MSW	REF.
CONVENTIONAL TECHNOLOGIES	Incineration	60-90	(Mukherjee et al., 2020)
	Anaerobic Digestion	22-55	
	Sanitary landfill	30-80	
	Composting	20-60	
NON-CONVENTIONAL TECHNOLOGIES	Pyrolysis	100	
	Gasification	40	
	Plasma gasification	300	
	MFC	271.36	(Nasrabadi & Moghimi, 2022)
	MEC	1185	(Lu & Ren, 2016)

4. Conclusion

Waste-to-energy (WTE) technologies include thermal, physical, biochemical, and bio-electrochemical technology. The selection of waste to energy (WTE) technologies needs consideration of energy efficiency, financial, and environmental aspects. The results of the assessment of existing technology show that anaerobic digestion and landfill have a low-cost and low potential for energy generation. Incineration has a low potential for energy generation and high CO_2 emissions and capital costs. Plasma gasification is superior in technical and environmental (high potential for energy generation, CGE, CCE, and H_2/CO, and low CO_2 emissions) and inferior in economical aspect (high capital and operating costs). MEC has a high H_2-potential for energy generation, low CO_2 emissions, and the highest capital cost. Thus, plasma gasification is the best technology for converting waste into energy and the selection of WTE technologies is influenced by energy efficiency, economic, and environmental factors.

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