Research Article

Synthesis Gas Production with Gasification Technology from Municipal Solid Waste

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Abstract

This study aims to develop, test performance, and evaluate the environmental pollution of garbage fuel with gasification technology. Heat conduction from municipal solid waste (MSW) burning from the gasification process was studied to dispose of solid waste and produce energy for communities. There were four types of solid waste in the total amount of 5 kg (including 0.5 kg of charcoal and firewood, 1.5 kg of paper, 2.0 kg of leaf litter, 0.5 kg of plastic, and 0.5 kg of others) with 2 tested ranges of average humidity: 10–20% and 50–55%. It was found that all waste could be converted for gas production with different gas amounts. From the experiment, dried MSW with 10–15% moisture content produced synthesis gas compositions (mole percent) that were H_2, CO_2, N_2, O_2, and CH4 at 1.9–2.4, 1.8–3.2, 56.5–60.2, 3.4–4.6, and 1.2–1.6, respectively. When fuel gas composition at the equivalent ratio between 0.2–0.34 was obtained from the MSW burning test with 10–15% average humidity, MSW burning in various equivalent ratios resulted in different amounts of synthesis gas. In addition, the optimal amounts of CH4 and the heating value of the gas were in the equivalent ratio of 0.28, and the highest production efficiency of synthetic gas (ηg) was 33.46%.

Keywords: Downdraft Gasification, Municipal Solid Waste, Pyrolysis Process, Synthesis gas

1 Introduction

Access to a clean, living environment and affordable, reliable energy are two of the most important issues facing developing countries. The abovementioned points coincide with the sustainable development goals SDG 7 and SDG 11 of the United Nations, respectively. Adopting a waste-to-energy system could leverage the possibility of reducing the adverse environmental impact occasioned by waste generation and ensuring the production of renewable and sustainable energy while achieving a circular economy [1]. In Thailand, the Ministry of Energy has set a target of 160 MW of waste electricity generation in 2022. We are facing waste management because a large amount of garbage overflows landfills. The more landfills arise, the more smell and sewage flowing occurs. The method of disposal is to be incinerated properly to reduce the environmental problem. Generally, before waste management, recycled waste is sorted and sold to a private recycling buyer/factory.

Two potential technologies are listed [1]: Refuse-derived fuel (RDF) technology is used for waste disposal of 150–300 tons per day, and gasification technology power plants use it to produce electricity. Thermal waste management can reduce the mass and volume of waste by 70–90% for waste disposal in the range of 500 tons per day [2]. Through thermal processes, gasification technology can efficiently reduce solid waste while being environmentally beneficial. The drawback of this technique is that the system's stability depends on how variable the solid waste is.

Gasification, a thermochemical process, applies a gasifying agent, turning feedstocks into a combustible gas called synthetic gas [2]. Therefore, an application of this technology as an auxiliary heat source in the gasification process can solve problems of variations in physical and chemical properties of solid waste because it can heat more than 1500 °C from the breakdown of various air molecules or gases, resulting in stable gasification system and highly effective in removing toxic elements in solid waste. In addition, gasification technology is a pollution-free incinerator to generate electricity by producing synthesized gas as fuel.

This study aims to study the method of municipal waste disposal for energy production by applying gasification to cope with variations of solid waste in physical and chemical properties. The results of this study add to the body of knowledge and advancement in the area of waste disposal technology invention for energy production. Additionally, by using municipal waste as fuel for the gasification process, we can learn technical viability from operation performance and know emission numbers of pollution and wastes in water and ashes, allowing us to develop a prototype for stable waste disposal technology and convert waste into energy.

2 Technology of Refuse-Derive Fuel

Refuse-Derived Fuel is not primarily aimed at eliminating or destroying solid waste to produce energy directly but also transforming solid waste by selecting elements with high energy into the process by sorting and converting it into a fuel that can be used for energy production [3]. Such technology has advantages. For instance, an RDF plant generally does not take up much space. Therefore, it can be installed near landfill areas without the need to transport solid waste. Besides, the resulting fuel can be stored and used to produce energy when needed.

The composition of synthesis gas is impacted by various garbage-related variables that are influenced by community and seasonal variations. In addition, this solid waste has low heating value and high ash and humidity, which is difficult for incineration plant designers and operators and makes it difficult to control environmental impacts. Processing solid waste through various management processes to improve physical and chemical properties of solid waste to turn it into RDF, which can be used as fuel to produce energy. Conversion of solid waste into fuel needs a management process, either more or less, depending on the desired properties of RDF [4]. The design of the solid waste treatment process depends on how to deal with waste; for instance, if garbage has already been sorted out of recyclable parts from its previous source, it may not be necessary to have a metal or glass sorting process in the process of processing waste into fuel.

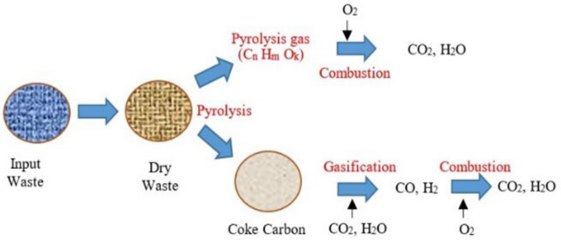

Figure 1: Waste disposal by a thermal process.

Waste incineration technology is the thermal decomposition of solid waste at high temperatures as thermal cracking [5]. This process requires heat from an external heat source to allow an endothermic process; then, there may be an oxidation reaction with an oxidizer to transform it into a product caused by complete combustion with such a process as an exothermal process allowing the use of heat obtained in energy production, or products made from thermal cracking may be processed to produce synthetic fuels for energy production, or burn with oxidizers to get heat before having energy. Waste disposal by the thermal process will be demonstrated in Figure 1.

3 Data Analysis

3.1 *Technology of pyrolysis gasification*

The technology of Pyrolysis/Gasification is coupled reaction. That is, when waste is dried by evaporation of humidity, it takes heat from the previous combustion, causing thermal crack and turning it into synthetic gas. At the same time, the oxidizer is often applied to the reaction area to facilitate partial combustion, causing heat from the reaction, which will be used in thermal cracking. Therefore, pyrolysis/gasification reactions often occur simultaneously. However, these reactions differ from incineration because their primary objective is not the destruction of solid waste but the conversion of solid waste in the form of solid fuel into a product that can be useful in the future. That is, gas fuel may use as fuel for an internal combustion engine, gas turbine engine, or direct burner in a steam generator or may be brought through various processes that are needed to synthesize to be liquid fuel or used in chemical industries. [6]

Definition of the gasification process or fuel gas production process is the process of solid fuel transformation containing hydrocarbons in the form of gas fuel, such as carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). This process is the thermochemical conversion process, which is a distillation of hydrocarbon elements by heating or steaming at high temperatures under partial oxidation at 1 atmospheric pressure or more. The reaction has several stages, both endothermic and exothermic reactions. The gas produced is called synthesis gas or producer gas [7]. Three types of fixed-bed furnaces have the same 4 gas production processes: drying, pyrolysis, combustion, and reduction process. Each process must occur relative to the others to generate synthesis gas. Therefore, the synthesis gas obtained from each furnace type will provide different qualities. The explanation of the synthesis gas production process is based on the process and location of the reaction taking place within the downstream kiln used in this research. The four-step details are as follows.

3.1.1 Drying zone process

The process of evaporating humidity from solid fuel at the top of the furnace is heated from the pyrolysis zone, steam and dry fuel obtained from the drying process will flow into the pyrolysis zone, below in the next zone. In this zone, the temperature is not high enough to cause the decomposition of volatile matter. The temperature in this zone is approximately 100–200 °C [8]. The temperature range in the drying zone will depend on the fuel types. The high-humidity fuel will affect the internal reaction zone and the synthesis gas properties. The processes occurring in this zone are given by Equation (1).

$$\text{Moist Fuel} + \text{Heat} \rightarrow \text{Steam} + \text{Dry Fuel} \tag{1}$$

3.1.2 Pyrolysis zone

The combustion zone heats the anaerobic thermal degradation process. This causes volatile matter, that is, the dry fuel component, to be dissolved from the solid fuel consisting of methanol, acetic acid, crude oil, and combustible and non-combustible gas. The temperature in this zone is approximately 200–600 °C [9]. The temperature range in the pyrolysis zone depends on fuel types. By-products from the pyrolysis process are charcoal and pyrolysis gas such as CO, CH_4, C_2H_6, and other hydrocarbon gases, as shown in Equation (2).

$$\text{Dry fuel} + \text{Steam} + \text{Heat} \rightarrow \text{Charcoal} + \text{Pyrolysis Gas} + \text{Steam} \tag{2}$$

3.1.3 Combustion zone

Pyrolysis gas and charcoal that pass through the combustion zone undergo oxidation with the air supplied to the combustion zone. In this combustion zone, carbon burns with a limited amount of oxygen. Through the combustion of pyrolysis gas and charcoal into the combustion zone, it will undergo oxidation with the air supplied to the combustion zone. In this field of combustion, partial combustion of carbon with oxygen will produce thermal energy for use in other reaction zones. The design of the combustion zone is very important for producing synthesis gas because the heat used in the synthesis process is only derived from the combustion zone [10]. The reaction in the combustion zone is exothermic. The temperature in this zone is approximately 1,100–1,500 °C. Therefore, heat and ash are mainly obtained from the reaction in the combustion zone. The processes occurring in the combustion zone are shown in Equation (3), and chemical reactions that occurred in the combustion zone are shown in Equations (4) and (5).

$$\text{Pyrolysis Gas} + \text{Charcoal} + \text{Steam} + \text{Air} \rightarrow \text{Product Gas} + \text{Charcoal} + \text{Steam} + \text{Heat} \tag{3}$$

$$C + O_2 \rightarrow CO_2 + \text{Heat} \tag{4}$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat} \tag{5}$$

3.1.4 Reduction zone

Air and CO fuel and residual pyrolysis gas from the combustion reaction in the combustion zone will flow into the reduction zone. The reaction in this zone converts steam gas into combustible synthesized gas [11]. Gas products from the combustion zone will continuously react in the reduction zone to produce combustible gas consisting of CO, H_2, and CH_4, which is concentrated enough for synthesis gas. The temperature in this zone is approximately 600–900 °C. The process in the reduction zone is shown in Equations (6) and (7).

$$\text{Product gas} + \text{charcoal} + \text{steam} + \text{heat} \rightarrow \text{synthesis gas} + \text{ash} + \text{steam} \tag{6}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 + \text{Heat} \tag{7}$$

In the final stage of biomass fuel production, the temperature in this zone will be between 600 and 700 °C. Fuel and gases such as CO, H_2, and CH_4 were generated, as shown in Equation (8).

$$C + 2H_2 \leftrightarrow CH_4 \tag{8}$$

3.2 *Equivalent ratio*

Equivalent Ratio [12] or ER value is a ratio of air weight to actual dry fuel weight compared with air weight ratio to theoretical fuel weight. The equivalent ratio is a ratio to evaluate the gasification process, which affects biomass gas's composition and calorific value. A suitable equivalent ratio of the gasification process should be between 0.2–0.4, which is partial combustion. Besides, the equivalent ratio is equal to 1 will cause complete combustion, and the temperature will rise quickly, as shown in the following Equation (9).

$$ER = \frac{[\text{Weight of oxidant/ Weight of dry fuel}]}{[\text{Oxidant /Fuel}]_{\text{(Stochiometric)}}} \tag{9}$$

The gasifier furnace's thermal efficiency (n_{th}) [4] is determined by the gas's calorific value of gas compared to the heating value (HV) of fuel, as shown in the following Equation (10).

$$\eta_{th} = \frac{Q_{gas} \times HV_{gas}}{FCR \times HV_{fuel}} \tag{10}$$

When

Q_{gas} is gas flow rate (m^3/min)

HV_{gas} is the calorific value of the gas (kJ/m^3)

FCR is fuel consumption rate (kg/min)

HV_{Fuel} is the calorific value of the fuel (kJ/kg)

The heating value of producer gas with kJ/m^3 [12] unit is the energy contained in each gas. Therefore, it can give a heating value and ignite measured by the concentration of CO obtained by sucking gas samples for analysis in a biomass gas meter. This is the main gas analyzed and studied in this research by substituting the amount of carbon monoxide in the heat equation as follows in Equation (11).

$$HV_{gas} = \left[(30 \times CO_2\%) + (25.7 \times H_2\%) + (85.4 \times CH_4\%)\right] \times 4.2 \tag{11}$$

When

CO% is the concentration of carbon monoxide (%vol)

H_2% is the concentration of hydrogen (%vol)

CH_4% is the concentration of methane (%vol)

Fuel consumption rate (FCR) [13] with kg/min unit is the weight of the fuel used in the experiment [Equation (12)].

$$FCR = \frac{\text{Weight of Used}}{\text{Operating time}} \tag{12}$$

When

Weight of Fuel Use is fuel weight (kg)

Operating Time is time (min)

4 Methods

4.1 *Design and result*

A gasifier is a device using thermal processes to convert organic matter containing carbon, hydrogen, and oxygen into a combustible fuel gas, such as CO, H_2, and CH_4 under oxygen limitation. Therefore, the design must consider saving: 1) Low energy consumption; 2) Less space for the machine; 3) Less investment than large systems; 4) Expand production conveniently and frequently; 5) Safe to operate; 6) Low internal air pressure; 7) Strong equipment structure and excellent durability; 8) Environmentally friendly [14].

Engineering theories in material strength and heat transfer were applied in design and calculation. Calculations were divided into 3 groups: furnace design, cyclone, cooler and additional accessories, such as equipment stand and temperature measuring socket as shown in Figure 2.

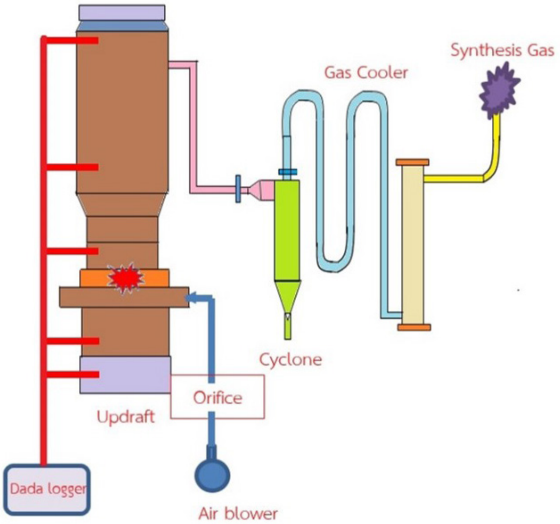

Figure 2: Gasifier system.

Figure 3: Gasifier furnace.

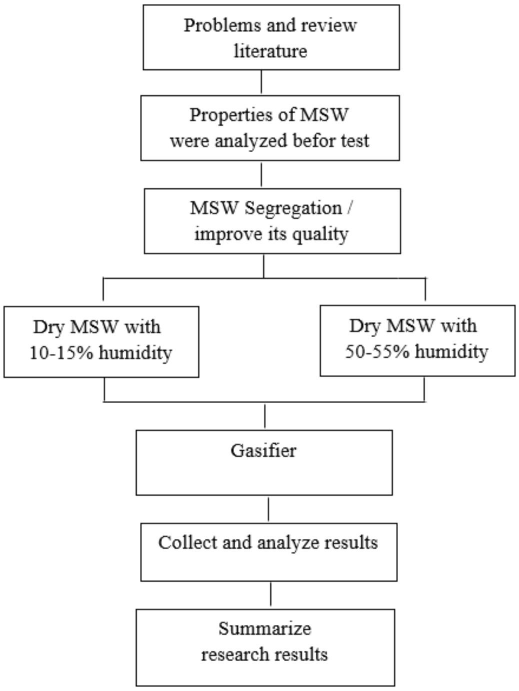

Figure 4: Steps that should be followed to implement this research program.

The size of the furnace is as follows. The furnace is 50 cm. The height of the furnace is 250 cm. The diameter of the air delivery pipe is ¾ inch. The diameter of the air nozzle is 4 mm. Therefore, the distance between the air blower and the air inlet is 13 cm. Besides, the length of the reduction zone is 39 cm or equal to the three-time length of the air inlet, and the combustion zone size is 26 cm or twice the length of the air inlet. The gasifier furnace is shown in Figure 3.

In this research, MSW from a municipality in Ratchaburi Province, Thailand, was used. Four types of municipal waste- charcoal and firewood, paper, leaf litter, and plastic were fuels for the combustion test. As Figure 4, Wastes were shredded into approximately 3–5 cm and then dried in the sun to reduce the moisture content of 5 kg MSW to 10–15% and 50–55%.

Next, solid waste was mixed to find an appropriate combustion rate. The steps are as follows. Firstly, solid waste is divided into two types: dry solid waste and wet solid waste. The moisture contents of wet and dry solid wastes are 50–55% and 10–15%, respectively. Secondly, garbage is collected in batches of 5 kg per set. Each set has a ratio of dry solid waste to wet solid waste of 1:0, 0:1, 1:2, and 1:1, in which each ratio is prepared to burn 4 batches with a known average.Four types of RDF–1 kg of 0.5 charcoal/firewood, 1.5 kg of paper, 2.0 kg of leaf litter, 0.5 kg of plastic, and 0.5 kg of others -were tested in the same amount of 5 kg with 2 ranges of average humidity: 10–15% and 50–55% with the following testing methods. First, the waste was heated for 15 min until the fuel at the bottom of the tank burnt thoroughly, then 5 kg of solid waste was put into the furnace and closed the lid until the white smoke appeared. Later, when white smoke turned brown, it indicated that some gas had started coming out. Since a continuation of gas for 20 min, smoke was even more intense continuously. When gas temperature from the furnace reached about 48 °C, it would be kept in a holding tank (It took about 4 min to store gas per tank). After 105 min, smoke started to diminish, and fire dimed. Therefore, gas collection had to stop. Two gas tanks could be stored during this period, counting time the gas could be ignited within 115 min.

It could be noticed that no more gas was released because fuel at the bottom of the tank had already burnt completely. After stopping the equipment and opening the lid, it was found that charcoal was completely combusted in the tank. This caused gas concentration to decrease until the flame went out. Next, the remaining ash and charcoal would be prepared for the next fuel tests. In portions of gas stored, it would be used as engine fuel for generating electricity further.

5 Result and Discussion

Table 1 shows the experiments of dry solid waste with 10–15% humidity: composition of 0.5 kg of firewood, 1.5 kg of paper, 2.0 kg of leaf litter, 0.5 kg of plastic, and 0.5 kg of others. Gas quantity in the typical gas tank is produced by burning waste in the furnace. Slightly different amounts of syngas were produced at 5 kg of garbage. The burning time was 4.41 min, with an average internal temperature of 554.5 °C. The average revealed that different gases were distributed differently. The gas storage tank had an average temperature of 36.2 °C. Gas CH_4 1.2–1.6% of a mol of H_2 1.8–3.2% mol CO_2 and 1.9–2.4% mol N_2, mol O_2, mol 3.4–4.6% part 80–310 ppm of H_2S.

Table 1: Experiments of dry solid waste with 10–15% humidity

Item	Gas Content in Standard Gas Cylinders (%mol)		An Average Temperature inside the Furnace (°C)	An Average Temperature at the Gas Storage Tank (°C)	Burning Time (Min)
1	CH_4	1.2–1.6	554.5	36.2	4.41
2	H_2	1.9–2.4			
3	CO_2	1.8–3.2			
4	N_2	56.5–60.2			
5	O_2	3.4–4.6			
6	H_2S (ppm)	8–310			

Table 2 shows the experiments of dry solid waste with 50–55% humidity consisting of 0.5 kg of firewood, 1.5 kg of paper, 2.0 kg of leaf litter, 0.5 kg of plastic, and 0.5 kg of others. The amount of syngas produced at 5 kg of garbage was slightly different during a burning time of 27.24 minutes at an internal temperature of the incinerator of 342.4 °C. It was determined from the average that other gases were distributed differently. The gas storage tank had a 32.6 °C average temperature. Gas CH_4 0.5–1.3% mol H_2 (%mol) 1.6–6.5 % mol CO_2 35–50% mol N_2 66–75 %mol O_2 1.4–8.5% mol 90–466 ppm of H_2.

Table 2: Experiments of dry solid waste with 50–55% humidity

Item	Gas Content in Standard Gas Cylinders (%mol)		An Average Temperature inside the Furnace (°C)	An Average Temperature at the Gas Storage Tank (°C)	Burning Time (Min)
1	CH_4	0.5–1.3	342.4	32.6	27.24
2	H_2	1.6–6.5			
3	CO_2	35–50			
4	N_2	66–75			
5	O_2	1.4–8.5			
6	H_2S (ppm)	90–466			

5.1 *Fuel gas content tests of two-type waste combustion at different periods*

Figure 5 shows the amount of gas (cubic meter or m^3) obtained in waste incineration per time (min). It can be seen that both types of waste combustion tests at the same amount of 5 kg resulted in a different amount of synthesis gas. The fuel with the most synthesis gas is dried solid waste of 10–15% humidity, and RDF composition is 0.5 kg of firewood, 1.5 kg of paper, 2.0 kg of leaf litter, 0.5 kg of plastic, and 0.5 kg of others. It can be seen that the synthesis gas from the combustion has different temperatures. Garbage with an average humidity of 10–15% and 50–55% had the highest gas amount of 2.438 m^3 and 1.665 m^3, respectively.

Figure 6 shows the fuel gas composition at the equivalent ratio of 0.2–0.34 obtained from the waste combustion test with an average humidity of 10–15%. It can be seen that different combustion at various equivalent ratios will yield different amounts of synthesis gas, and a high amount of CH_4 was in the equal ratio of 0.28 ± 0.012.

From Figure 7: The calorific value of the fuel gas at the equivalent ratio (0.2–0.34), it can be seen that the optimum high heat conductivity of the gas is at the ER

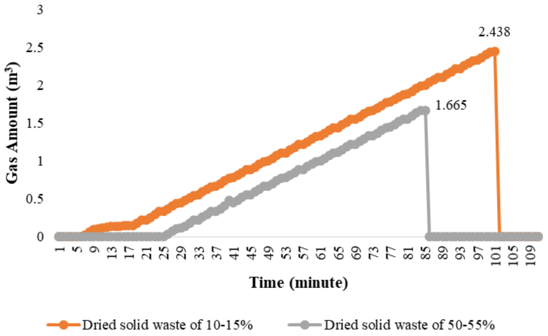

Figure 5: Fuel gas content tests of two-type wastes combustion at different periods.

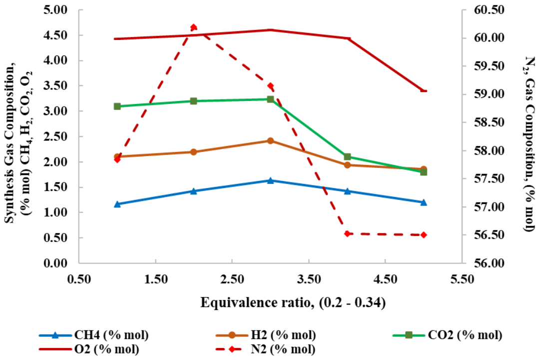

Figure 6: Composition of the fuel gas at the equivalent ratio = (0.2–0.34).

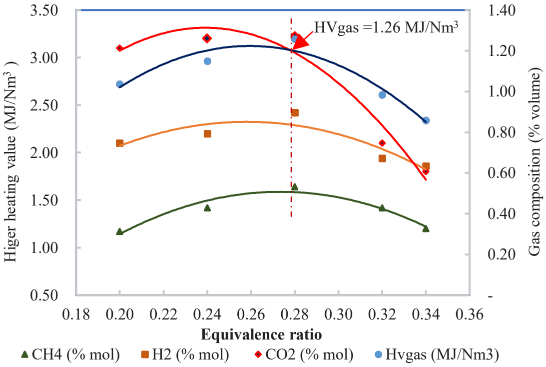

Figure 7: The calorific value of the fuel gas at the equivalent ratio (0.2–0.34).

of 0.28, in which the range is considered the highest CH_4 gas range, and the amount of H_2 started to decrease with the CO_2 amount decreasing as well. From a recent study for catalyst development in thermochemical conversion of MSW, 900 °C MSW activated energy of pyrolysis and reduced by iron salts. The reactor was thermogravimetric analysis (TGA) [15]. MSW pyrolysis and iron ore reduction were proposed as a combined process. After running TGA experiments and fitting kinetic data, it was found that the activation energy for the pyrolysis of MSW was 180.32 kJ/mol. The activation energy was decreased by iron ore and iron oxide to 151.76 and 150.18 kJ/mol, respectively. Hydrolysis gas and tar are catalyzed by iron ore and iron oxide [12]. For an integrated process for MSW gasification, 677–877 °C MSW with C 48.81%; H 6.86%; O 41.09%; N 2.78%; S 0.46% was burnt via the process of down-draft fixed bed gasifier, gas turbine, organic Rankine cycle [15]. The optimum powers for steam, air, and oxygen gasifying agents were 281.1 kW, 279.4 kW, and 266.9 kW, respectively. At all gasification temperatures and low moisture concentrations, the hydrogen content of steam was increased. At high moisture concentrations, the oxygen medium's H_2 content was greater [15].

6 Conclusions

The experiment results using each type of biomass gas in the equipment are as follows. Four types of solid waste in the amount of 5 kg, including 0.5 kg. of firewood, 1.5 kg. of paper, 2.0 kg. of leaf litter, 0.5 kg. of plastic, and 0.5 kg. of others with 2 ranges of average humidity: 10–15% and 50–55%, were tested. The results showed that all of them could be used as a fuel for synthesis gas production with different gas content results. For example, from the experiment of dry solid waste with 10–15% humidity, the waste composition of 0.5 kg. of firewood, 1.5 kg. of paper, 2.0 kg. of leaf litter, 0.5 kg. of plastic, and 0.5 kg. of other will get synthesis gas percent by a mole at 1.2–1.6, 1.9–2.4, 1.8–3.2, 56.5–60.2, and 3.4–4.6, respectively.

When considering the fuel gas composition at the equivalent ratio (0.2–0.34) obtained from the waste combustion test with 10–15%average humidity, it can be seen that the burning of garbage in various equivalent ratios will result in different amounts of synthesis gas. From the test, it was found that the optimal amount of CH_4 gas and the heating value of the gas will get a large quantity in the ER = 0.28, and the highest production efficiency of synthesis gas was 33.46%. It can be summarized that low humidity results in good combustion efficiency and more gas, and humidity has a direct impact on combustion and gas quality.

From previous tests of RDF combustion, it has been found that waste segregation is important, which affects the synthesis gas production, such as types and amount of waste, as well as the humidity of each kind of waste [16]. A gasifier furnace designed to produce synthesis gas with gasification technology from municipal waste is an alternative way to reduce the amount of waste in the community of Thailand. However, it needs to develop an automated system for waste sorting to control waste types and humidity. Furthermore, solid waste must be managed effectively to lessen potential negative effects on human health and the environment. However, there are several problems with how solid waste is currently managed. To address the issues with the current methods, it is essential to build efficient waste management systems using cutting-edge technologies.

It was discovered that waste separation is essential because it influences the production of syngas and influences the type, quantity, and moisture content of each form of waste. The amount of syngas produced by burning garbage at different equivalence ratios would vary. [16] According to the test, the gas with the highest calorific value and CH_4 content was the best. In the equivalent ratio ER = 0.28, it will be a significant amount. The maximum production efficiency for synthesis gas is 33.46%. When each sort of waste is burned, it is discovered that they may all be utilized as fuel to create syngas. This will provide the values of various gas amounts as a result.

Author Contributions

P.K.: investigation, reviewing and editing; A.S.: investigation, methodology, writing an original draft; research design, data analysis, data curation and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

Generally, there is a conflict between people engaged in garbage collection, and employees of local government organizations competing for solid waste that can be sold for money.

Abbreviations

°C	Degree Celsius
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ER	Equivalent Ratio
FCR	Fuel Consumption Rate
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HV	Heating Value
N_2	Nitrogen
ηg	Synthetic Gas
O_2	Oxygen
kg.	Kilogram
M^3	Cubic Meter
MJ/Nm^3	Megajoules Per Newton Cubic Meter
MSW	Municipal Solid Waste
PPM	Part Per Million
RDF	Refuse-derived Fuel
SDG	Sustainable Development Goal
TGA	Thermogravimetric Analysis
ηth	Thermal Efficiency

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