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Flexible Feedstock Analysis of Biomass Gasification Process for Carbon-Negative Energy Technology via Aspen Plus Simulation

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The escalating concern over greenhouse gas (GHG) emissions from solid waste treatment and fossil fuel power plants has garnered global attention, including in Malaysia. Abundant agricultural waste (AW) and organic municipal solid waste (MSW) in this region hold promise as potential replacements for fossil fuels, offering a pathway to generate electricity while reducing GHG emissions. The innovative gasification approach, particularly the combined heat and power (CHP) system, emerges as a viable solution to address these challenges. However, the operational design of conventional gasification processes typically using a single type of fuel from various discarded resources, such as agricultural waste (e.g., woodchips and coconut shells) and organic MSW, remains controversial. To address these concerns, the present study investigates the power pallet system's capability and reliability to generate electricity from diverse mixed ratios of organic MSW to agricultural waste via a simulation approach. The results demonstrated that power generation remained above 20kW for all mix ratios. It was observed that as the ratio of MSW increased, the composition of hydrogen and carbon monoxide decreased. These trends suggest that power generation is influenced by the syngas yield, which correlates with the quality of the feedstock.

Keywords: Carbon-negative energy; feedstock flexibility; gasification; renewable energy

I. INTRODUCTION

Emission of greenhouse gases (GHG) from solid waste treatment and fossil fuel power plants has been a major concern in Malaysia as well as globally. Malaysia relies on fossil fuels, especially oil, natural gas, and coal, to generate electricity (Yunus, 2017). The burning of fossil fuels for energy production is a major contributor to GHG emissions, with carbon dioxide (CO_2) being the most significant greenhouse gas, responsible for around 76% of total emissions from human activities (EIA, 2023). Furthermore, the decay of organic matter of municipal solid waste (MSW) and agriculture wastes (AW) in landfills would produce methane (CH_4) gas, which could also contribute to extreme global warming and other environmental issues (EIA, 2023). The discarded AW and organic MSW, which are abundant in Malaysia, have the potential to replace fossil fuels to generate electricity as well as to reduce GHG emissions.

Waste-to-Energy (WtE) technology emerges as a potential approach to convert these wastes to energy via various processes such as gasification and pyrolysis. Gasification can be defined as a thermochemical process that involves the conversion of solid or liquid feedstock, which is carbonaceous materials, into gaseous fuel known as syngas (Lan *et al.*, 2018). In order to obtain syngas from the gasification process, it is necessary to react the carbonaceous material at high temperature with the presence of gasifying agents such as steam or oxygen (O_2). For example, in the gasification of biomass, solid and gaseous mixtures are produced in the outlet of the unit operation, which contains hydrogen (H_2), carbon monoxide (CO), CO_2, a small amount of CH_4, light hydrocarbons, tar, char, ash, and minor contaminants. These products are known as 'raw syngas' (Mikulandrić *et al.*, 2016).

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Furthermore, pyrolysis, which precedes gasification, is an extremely complex reaction that can ideally be defined as a thermal degradation process that involves the breakdown of larger hydrocarbons into the combination of solids, liquids, and gases (La Villetta *et al.*, 2017). Pyrolysis is one of the important processes as the product release through pyrolysis holds an important role in acting as the reactant for all the other chemical reactions that take place in the next processes, which are combustion, cracking, and reduction (Fernando *et al.*, 2016). Despite its advantages toward the sustainability of the environment, the gasification process encounters several issues in terms of the gas conversion efficiency to produce quality syngas. This is because of the large number of chemical reactions are influenced by several factors, such as the characteristics of the feedstock and the operational temperature of the processes. Additionally, from the energy point of view, the inherent properties of agriculture wastes and MSW give significant challenges in a large-scale plant adopting WtE technology, as their characteristics can lead to operational and technical issues.

Numerous studies on gasifiers have explored the utilisation of mixed feedstocks, highlighting their potential in optimising resource utilisation for electric power generation. (Bhoi *et al.*, 2018) conducted a study where they employed a commercial-scale downdraft gasifier to gasify a combination of MSW and switchgrass as feedstock. They experimented with mixture ratios of 0%, 20%, and 40% to produce power. Their findings revealed a notable decrease in the composition of CO, with levels dropping from 16.7% at a 0% mix ratio of MSW to 12.6% and 14.1% at 20% and 40% mix ratios of MSW, respectively. This reduction was attributed to the lower carbon content in the higher MSW mix ratios, while levels of H2 and hydrocarbon compounds increased with higher MSW mix ratios (Bhoi *et al.*, 2018). The study also reported a marginal decrease in CO2 with increasing mix ratios, and the heating values of the syngas obtained were 6.2 MJ/Nm3, 6.5 MJ/Nm3, and 6.7 MJ/Nm3 for each mix ratio, respectively.

In a separate study, Indrawan *et al.* (2018) investigated power generation through the gasification of two mixed resources, MSW and switchgrass, used as feedstock. Their research employed a patented design featuring a 60 kW downdraft gasifier and an internal combustion engine. The exploration encompassed various ratios, including 0%, 20%, and 40%. Their findings indicated a decrease in CO levels at higher mix ratios, concurrent with an increase in H2 levels. However, a distinct result emerged in terms of CO2, which exhibited a slight increase with higher mix ratios. Simultaneously, the heating values of the syngas produced at mix ratios of 0%, 20%, and 40% were measured at 6.91 MJ/Nm3, 7.74 MJ/Nm3, and 6.78 MJ/Nm3, respectively (Indrawan *et al.*, 2018). This research work represents a significant step in addressing the existing research gap, as it conducts a comprehensive assessment of the feasibility and practicality of harnessing Malaysia's AW and organic MSW to produce high-quality syngas. This syngas holds great potential for efficient power generation, making it a promising avenue for sustainable energy solutions. As a result, this paper paved the way forward to a carbon-negative energy technology that is feasible for long-term operation. Subsequently, contributes to the commitment of the government to reducing greenhouse gas emissions and eliminating environmental impact.

II. MATERIALS AND METHOD

A. *Characterisation Analysis*

1. *Material preparation*

Figure 1 illustrates the schematic diagram of the gasification process. The selected feedstock for this study includes MSW and woodchips, both of which undergo pre-treatment before utilisation. These materials were chosen based on their physiochemical properties, characterised by high calorific values, and their abundant availability, making them valuable renewable resources.

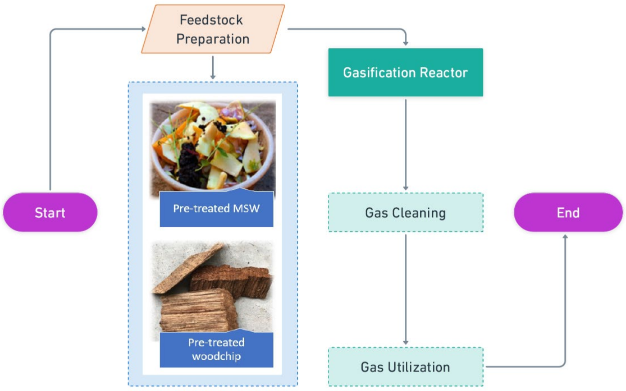

Figure 1. Pre-treated organic MSW.

Both types of feedstock are prepared to the size and moisture content that suits the design specification of the gasification with the CHP system. Once the feedstocks are sorted, they undergo a drying process until their moisture content is reduced to less than 20%. Subsequently, both feedstocks are then cut into smaller pieces, with dimensions ranging between 3cm to 5cm, to facilitate efficient gasification. Six samples with different mix ratios are then prepared, with detailed information on the feedstock compositions provided in Table 1.

Table 1. Mix ratio compositions of each sample.

Sample	Composition
Sample A	100% Woodchip
Sample B	20% organic MSW + 80% Woodchip
Sample C	40% organic MSW + 60% Woodchip
Sample D	60% organic MSW + 40% Woodchip
Sample E	80% organic MSW + 20% Woodchip
Sample F	100% organic MSW

B. Proximate and Ultimate Analyses

The characterisation data of feedstock is done by conducting the proximate and ultimate analysis. The characterisation data of each sample are obtained through a regression model adopted from Japan's National Urban Cleaning Conference, Waste Treatment Facility Planning and Design Guidelines, 2017 (Waste Treatment Facility Planning and Design Guideline, 2017). Proximate analysis is conducted to determine the moisture content, volatile matter, fixed carbon, and ash content. While ultimate analysis is conducted to determine the carbon, hydrogen, oxygen, nitrogen, sulphur, and chlorine content at each mixing ratio. The low heating value of each sample is also being determined.

1. Regression model

For the input characterisation data of the simulation, the ultimate analysis data of each sample is derived based on regression mode subjected to different mix ratios. The elemental composition of mixed waste can be determined based on equations (1) – (7) (Waste Treatment Facility Planning and Design Guideline, 2017).

$$\text{Carbon, } C = (0.4223 \times Pa\% + 0.7187 \times P\% + 0.4531 \times Ga\% + 0.5092 \times Ce\% + 0.4769 \times Ba\% + 0.3586 \times Rr\%) \times (1 - W/100) \quad (1)$$

$$\text{Hydrogen, } H = (0.0622 \times Pa\% + 0.1097 \times P\% + 0.0605 \times Ga\% + 0.0656 \times Ce\% + 0.0604 \times Ba\% + 0.0461 \times Rr\%) \times (1 - W/100) \quad (2)$$

$$\text{Nitrogen, } N = (0.0028 \times Pa\% + 0.0042 \times P\% + 0.0289 \times Ga\% + 0.0292 \times Ce\% + 0.0084 \times Ba\% + 0.0181 \times Rr\%) \times (1 - W/100) \quad (3)$$

$$\text{Sulphur, } S = (0.0001 \times Pa\% + 0.0003 \times P\% + 0.0010 \times Ga\% + 0.0012 \times Ce\% + 0.0001 \times Ba\% + 0.0004 \times Rr\%) \times (1 - W/100) \quad (4)$$

$$\text{Chlorine, } Cl = (0.0017 \times Pa\% + 0.0266 \times P\% + 0.0025 \times Ga\% + 0.0045 \times Ce\% + 0.0018 \times Ba\% + 0.0022 \times Rr\%) \times (1 - W/100) \quad (5)$$

$$\text{Combustible, } V = (0.8931 \times Pa\% + 0.9512 \times P\% + 0.8684 \times Ga\% + 0.9786 \times Ce\% + 0.9375 \times Ba\% + 0.6778 \times Rr\%) \times (1 - W/100) \quad (6)$$

$$\text{Oxygen, } O = V - (C + H + N + S + Cl) \quad (7)$$

Whereby,
Pa: Paper
P: Plastic
Ga: Organic MSW
Ce: Fibre/Cloth
Ba: Wood
Rr: Others

While the Low Heating Value (LHV) can be derived based on the equation (8):

$$LHV = 190B - 25W \text{ (kJ/kg)} \quad (8)$$

Whereby,
B: Combustibles in waste
W: Moisture Content of waste

C. Flowsheet Development

In this study, a flowsheet model of a downdraft gasification with CHP system using mixed organic MSW and woodchip as feedstock is developed in Aspen Plus software based on the actual 20-kW power pallet unit. The 20-kW power pallet used in the development of the flowsheet model consists of a downdraft gasifier equipped with spark a fired internal combustion engine (ICE), cyclone, air filtration, flare system, and process control unit (PCU). This power pallet unit - was manufactured by All Power Labs and is physically available at EGT 05 lab in Universiti Teknologi Malaysia, Kuala Lumpur. A simulation is conducted using feedstock with a mix ratio of organic MSW and woodchip at 0%, 20%, 40%, 60%, 80% and 100%.

III. RESULT AND DISCUSSION

Simulation in Aspen Plus software consists of a few requirements to simulate the model accurately. These requirements include the specification of feedstock, which is mixed MSW and woodchip at various mix ratios. It is based on its operating conditions, amount or flow rate, and the component attributes, which are proximate and ultimate data since MSW and woodchip are non-conventional components. The moisture content of feedstock at each mix ratio before the drying process is set at 0.2 since the power pallet is capable to withstand a maximum moisture content of 20%. The expected flow rate and other parameters of feedstock condition are listed in Table 2.

Table 2. Operating conditions and flow rate of feedstock for the gasifier (All Power Labs, 2017).

Parameter	**Value**
Temperature	25°C
Pressure	1 atm
Flow Rate	80gm/sec
Maximum Moisture Content	20%

Based on this requirement, the ultimate analysis data and low heating value of feedstock at each mix ratio are obtained based on the equation (1) – (8) of a regression model. The characterisation result is shown in Table 3. The developed flowsheet model is divided into two process boundaries, which are the gasification process and the power generation process (CHP), as illustrated in Figure 2. Detailed of the flowsheet model development is available in (Kamaruzaman *et al.*, 2023).

Table 3. Proximate analysis and ultimate analysis data of mix ratio feedstock.

Parameter	**100% Woodchip**	**20% MSW + 80% Woodchip**	**40% MSW + 60% Woodchip**	**60% MSW + 40% Woodchip**	**80% MSW + 20% Woodchip**	**100% MSW**
Proximate Analysis						
Fixed Carbon, FC (%)	75.00	73.89	72.79	71.68	70.58	69.47
Volatile Matter, VM (%)						
Ash Content, AC (%)	25.00	26.11	27.21	28.32	29.42	30.53
Ultimate Analysis						
Carbon, C (%)	38.15	37.77	37.39	37.01	36.63	36.25
Hydrogen, H (%)	4.83	4.83	4.84	4.84	4.84	4.84
Oxygen, O (%)	31.19	30.11	29.03	27.95	26.87	25.79
Nitrogen, N (%)	0.67	1.00	1.33	1.66	1.98	2.31
Sulphur, S (%)	0.01	0.02	0.04	0.05	0.07	0.08
Chlorine, Cl (%)	0.14	0.16	0.17	0.18	0.19	0.20
Low Heating Value, LHV (MJ/kg)	13.75	13.54	13.33	13.12	12.91	12.70

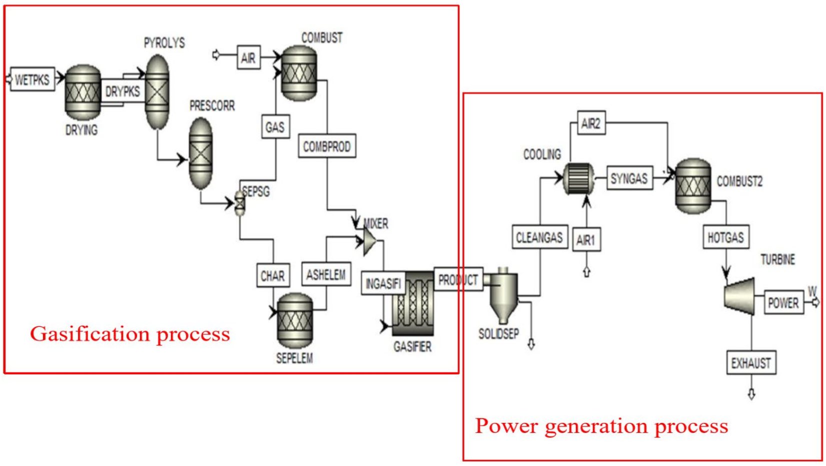

Figure 2. Simulation flowsheet of mixed MSW & Woodchip gasification with CHP system.

The mass fraction of syngas and the power generation obtained from the gasification process at each mixing ratio is illustrated in Figure 3. The result shows an insignificant difference between each sample in terms of CO, H_2, and power output. H_2 started to decrease at a ratio of 80% WC & 20% MSW and further decreased at a ratio of 20% WC & 80% MSW. Meanwhile, it can be seen that the CO only decreased at a ratio of 20% WC & 80% MSW. Power generation is directly affected by syngas yield and quality (Indrawan *et al.*, 2018). From the result, even though the power generation was marginally decreased at a ratio of 60% WC & 40% MSW and further decreased at a ratio of 100% MSW, the power generated by each mix ratio was still above 20kW.

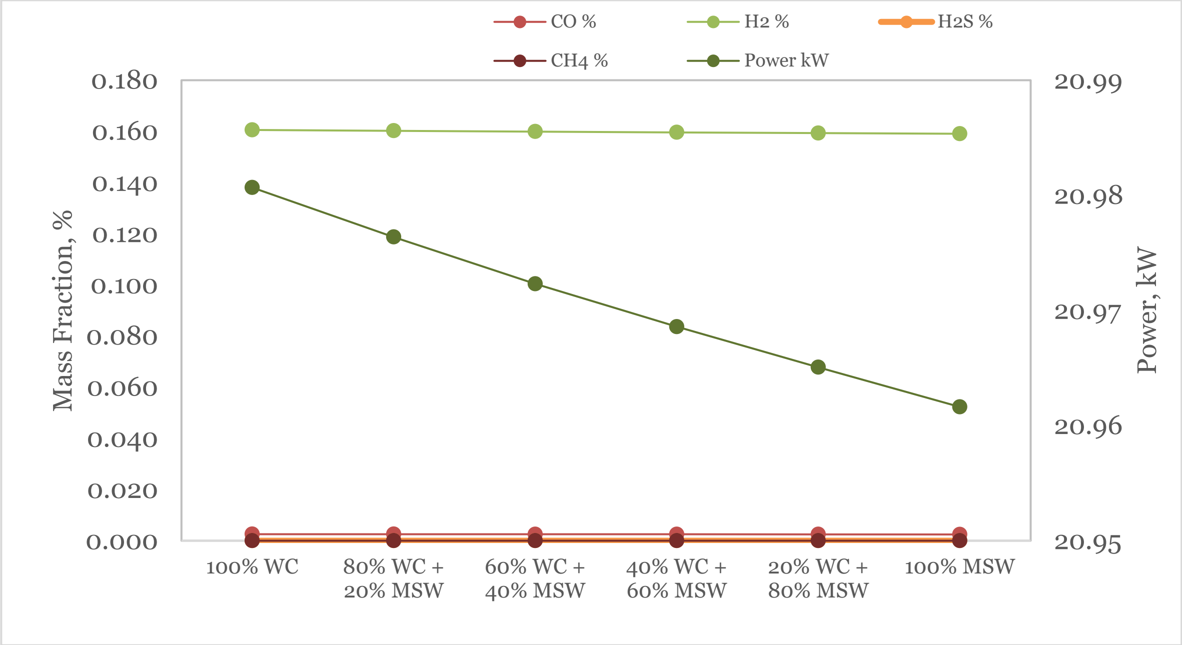

Figure 3. Composition of syngas from the gasification process at each mix ratio.

IV. CONCLUSION

The discarded agriculture waste and organic municipal solid waste, which are abundant in this country, has the potential to replace fossil fuel to generate electricity as well as to reduce GHG emission. This work has successfully demonstrated the potential of utilising discarded mixed waste, which is abundant in the country, as a replacement for fossil fuels in electricity generation and reducing greenhouse gas (GHG) emissions. This study highlights the significance of power generation remaining above 20kW for all mix ratios, which is noteworthy as it suggests a relatively consistent power output even with varying waste compositions. However, a notable trend can be observed, where H_2 decreases as the ratio of MSW increases, and CO decreases significantly at a higher MSW ratio. These trends suggested that power generation is affected by syngas yield and quality, which correlate with the feedstock properties.

V. ACKNOWLEDGEMENT

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